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DETERMINATION OF FACTORS WHICH INFLUENCE THE DRAPING PROPERTIES OF COTTON FABRICS

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DETERMINATION OF FACTORS WHICH INFLUENCE THE DRAPING PROPERTIES OF COTTON FABRICS

by

Chauncey C. Chu, Walter J. Hamburger, and Milton M. Platt
Fabric Research Laboratories, Inc.

A report of research conducted for the U. S. Department of Agriculture under a Research and Marketing Act Contract. The project was a part of the broad program of research on cotton utilization which is in progress at the Southern Utilization Research and Development Division, Agricultural Research Service.

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ERRATA

Page 6, column 1, equation 5 should be:

$$\omega = \frac{2v_W}{D_p} = \frac{2v_T}{D_p} \sin \theta = \frac{2r\omega_T}{D_p} \sin \theta$$

Page 6, column 1, equation 7 should be:

$$\omega = \frac{2r\omega_T}{D_p} \frac{r}{C} = \frac{2\omega_T}{CD_p} r^2$$

Page 6, column 1, equation 10 should be:

$$\Phi = \int \omega dt = \frac{2}{CD_p} \int r^2 \frac{d\theta}{dt} dt = \frac{2}{CD_p} \int_0^{2\pi} r^2 d\theta = \frac{4}{CD_p} \int_0^{2\pi} \frac{r^2}{2} d\theta$$

Page 6, column 2, line 8 should be: and $\frac{2}{\pi CD_p}$ is the number of revolutions per unit area.

Page 6, column 2, line 18 should be:

$$\frac{2}{\pi CD_p} = \frac{2}{\pi(0.772)C} = 0.1$$

Page 15, column 1, equation 15 should be:

$$y = \frac{3w}{16Et^3} \left[\frac{7a^6 + b^6 - a^4b^2 - 7a^2b^4 - 4a^2b^2(5a^2 + b^2)\ln\frac{a}{b} - 16a^4b^2(\ln\frac{a}{b})^2}{a^2 + b^2} \right]$$

Page 15, column 2, footnote to Table 9 should be:

$$\alpha = \frac{3}{16} \left[\frac{7 + \beta^6 - 7\beta^4 - \beta^2 + 4\beta^2(5 + \beta^2)\ln\beta - 16\beta^2(\ln\beta)^2}{1 + \beta^2} \right]$$

Page 17, column 1, equation 30 should be:

$$k = \frac{\sqrt{(a - b)^2 - (x - b)^2}}{a^4}$$

Page 21, column 1, following equation 47 should be:

where a = Radius of sample, inches.
b = Radius of support, inches.

Page 29, column 1, equation 89 should be:

$$\frac{r_o}{r} = \left[\left(\frac{\lambda}{4h} + \frac{h}{\lambda} \right) \right] \sin^{-1} \frac{1}{\frac{\lambda}{4h} + \frac{h}{\lambda}}$$

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I. INTRODUCTION AND SUMMARY

The term "drape," or "drapability," is usually considered as the characteristic of a fabric by which it adjusts into folds or pleats when acted on by force of gravity. Hence, a fabric is said to have good draping qualities when the configuration is graceful and pleasing to the eye. Obviously, then, the word "drape" is a qualitative term. Since drape is of great practical significance, it is important that it be measured quantitatively.

Numerous "drape tests" have been reported in the literature, but none have presented any correlation between their data and subjective evaluations. This is largely due to the failure to recognize that "drape" is not necessarily determined conclusively by tests involving monoplanar curvature of the fabric samples, such as in beam type tests. (These tests are typified by the "Drapeometer" and "loop" tests of various shapes.) The present day beam type tests are incapable of differentiating between the degree of firmness of drapery and paper; i.e., it is possible to select a piece of paper and a piece of fabric both having the same bending properties, yet it is doubtful that the paper will drape as well as the cloth. One is acquainted with children's party costumes made of crepe or tissue paper; regardless of how flexible the paper may be, it does not have the same appearance as cloth—it is seldom graceful. In other words, it does not drape!

It is obvious from the above discussion that an instrument capable of distorting the sample, naturally, by its own weight, into multiplanar curvature is necessary if drape is to be evaluated quantitatively. The drapability of yard goods samples is usually displayed in store windows by draping them over circular pedestals. This method simulates service conditions, as a cape draped over the shoulders or a skirt around the hips of the wearer. The F.R.L. Drapemeter[1] was designed on a similar principle. Section II of this report describes in detail the working principles, construction, and operating procedure of this instrument.

To determine the validity of the Drapemeter for measuring drapability, a subjective evaluation study was conducted in which a comparison was made between the experimental data and the subjective visual and tactile rankings of fabric drapability. Following a general survey of opinions, a number of fabric samples were purchased and tested in the laboratory. Ten of these fabrics were submitted to 66 respondents for evaluation, 57 of whom made full evaluations between the extremes. The rankings of these 57 respondents were found to be in good agreement with the Drapemeter rankings, thereby substantiating its designed function. Data and discussions on the subjective evaluation study are given in Section III.

Attempts were made to analyze the mechanism of draped samples, i. e., fabrics under multiplanar curvature, on the basis of the classical theories of mechanics. The subjects investigated in these studies include the application of the flat plate theory on deformation; derivation of a logical basis for comparison of experimental results made under different test conditions; analyses of the geometry of the draped specimen or its projected diagram; study of the factors influencing the stiffness of fabrics. To a large extent, these investigations were fruitful; however, much additional work must be done to fully understand the complete mechanism of drape. Descriptions of the foregoing analyses are given in Section IV.

With the instrument field tested and an introductory theoretical background established, research was begun on the "Determination of Factors Which Influence the Draping Properties of Cotton Fabrics" (Section V). This research called for experimental data on cotton fabrics with systematic variations in structure. Unfortunately, such fabrics were commercially unavailable and the research contract did not provide funds for the manufacture of experimental fabrics. Under the circumstances, "model" fabrics woven from cellulose-acetate yarns and containing systematic geometric variations were studied first. Subsequently, a few cotton fabrics with geometric variations were obtained. Since the results of geometric variation in using either type of material were in good agreement, conclusions could be drawn concerning the effects of structure on drapability.

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[1] The Drapemeter; its utilization; and the information of this report on its principles, operation, and construction are the exclusive property of Fabric Research Laboratories, Inc., who are securing patents and copyrights. The use of this instrument in the U. S. Department of Agriculture research is permitted, but is not to be construed as a waiver of any proprietary rights of Fabric Research Laboratories, Inc.

Section VI of this report gives the present status of the research to date. The fabric structures necessary for good drapability are given in qualitative terms. Additional studies to further the research are also proposed.

II. THE DRAPEMETER

The Drapemeter measures fabric drape while the fabric is distorted into a surface exhibiting compound curvature. If a circular fabric sample, of diameter D, (Figure 1, diagrams (i) and (ii) is draped over a support of diameter d, then the overhang around the periphery is ½ (D — d). Unless the material is extremely rigid, the overhang must deform under its own weight. Consider Figure 1, where the overhang before deformation is represented by diagram (iii). Under the draped condition, the deformed sample takes the form of diagram (iv). The index of drapability or the Drape Coefficient, F, is: $F = \frac{A}{A_D - A_d}$ where A, A_d, and A_D are the areas shown on Figure 1.

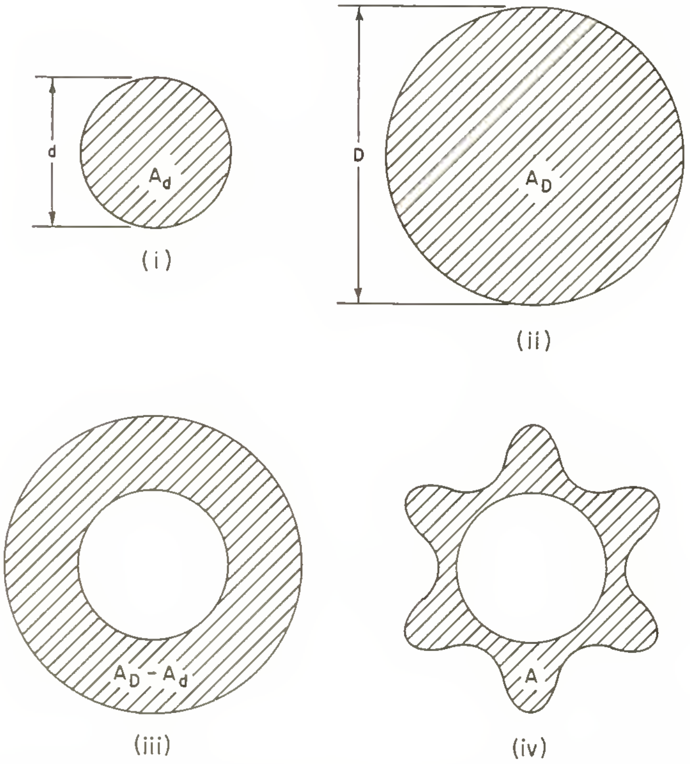


Figure 1.—Components Of The Drape.

The details of the instrument follow:

A. Working Principles

The problem of determining the projected area of a draped sample was solved as described below and as diagrammed in Figure 2.

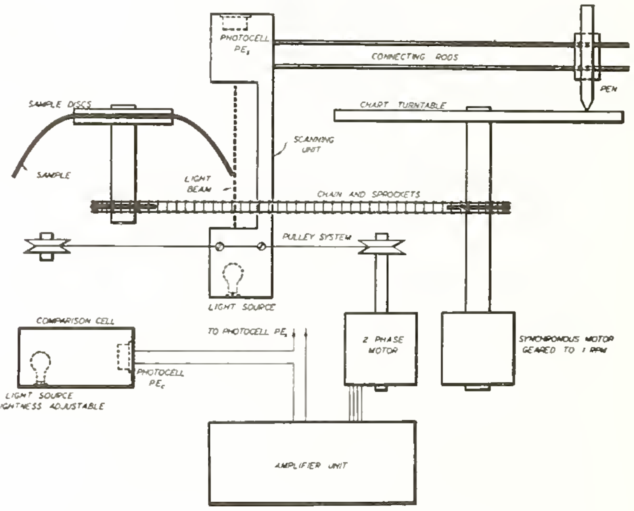


Figure 2.—Schematic Diagram of the F. R. L. Drape-Drapemeter.

One of two synchronized turntables supports the draped sample, and a standard circular chart is mounted on the other. A light beam from a small lamp is focused on a photocell, both elements being mounted in a movable unit. This optical system scans the draped sample and automatically and continuously positions itself at the edge of the fabric. The movements of the photocell are recorded on the chart by a pen mounted in a carriage which is mechanically connected to the scanning unit. Thus, when the turntables have performed one complete revolution, an accurate vertical projection of the draped sample is drawn on the circular chart.

B. Analysis of Instrument

1. Optical System

The components used in the optical system are two photocells of the photovoltaic type, two lamps, a filament transformer, a potentiometer, and a collimating lens.

One photocell, P. E.$_c$, used as a comparison cell, is illuminated by a lamp connected to the filament transformer through a potentiometer. The scanning cell, P. E.$_s$, receives the light from a second lamp through a collimating lens. The brightness of the lamp in the comparison unit is adjusted until the light falling on the comparison cell is approximately equivalent to the light which falls on the scanning cell when the beam is cut in half by the edge of the samples. The outputs of the two cells are bucked against each other in a series connection and the algebraic difference in their voltages is applied to the input of an amplifier. When the illumination is equal on both cells, their combined output is zero. If the illumination on the scanning cell be increased or decreased owing to the rotation of the irregular projection of the sample, the output will become either a positive or negative voltage. This output, amplified by an electronic system containing a phase sensitive circuit, controls one phase of a two-phase motor which positions the scanning unit so as to restore the electrical balance between the scanning cell and the comparison cell. Then as the sample and chart revolve synchronously, the amplifier and motor combination moves the scanning device so as to keep the light on the P. E.$_s$, equal to that which will balance out the output of the comparison cell, whose illumination is fixed.

2. Mechanical Operation

A synchronous motor, geared down to 1 revolution per minute, drives the chart table and also, by means of sprocket gears and a roller chain, turns the sample. Disks up to 10 inches in diameter may be used to hold the sample, depending upon the sample characteristics, as described later in this report. In order to place the sample on the disk without distortion, the shaft of the sample turntable may be slid down until the disk is flush with the cabinet base. Once the sample is in place, the table is raised to its proper operating position, with the sample disk as close to the photocell as possible.

The turntable which holds the chart is 12 inches in diameter and has a small vertically projecting knob positioned about ½ inch off center to keep the paper from slipping as the table revolves. Standard circular charts may be used.

A two-phase motor, driven by the amplifier output and connected to a wire and pulley system, moves the scanning unit along a straight line between turntable centers. The direction of rotation of the motor is such that the scanner is moved until the edge of the fabric cuts the light beam and the light reaching the moving cell is equal to that incident upon the fixed cell. Connected to the scanner by two horizontal rods is a pen carriage which holds the pen on the line between turntable centers. Thus the radial movements of the scanning unit at the rotating sample are exactly duplicated by the radial motion of the pen on the rotating chart. Table rotation starts by manually depressing the repeat button shown in Figure 3. The disks are automatically stopped by a limit switch after each complete revolution.

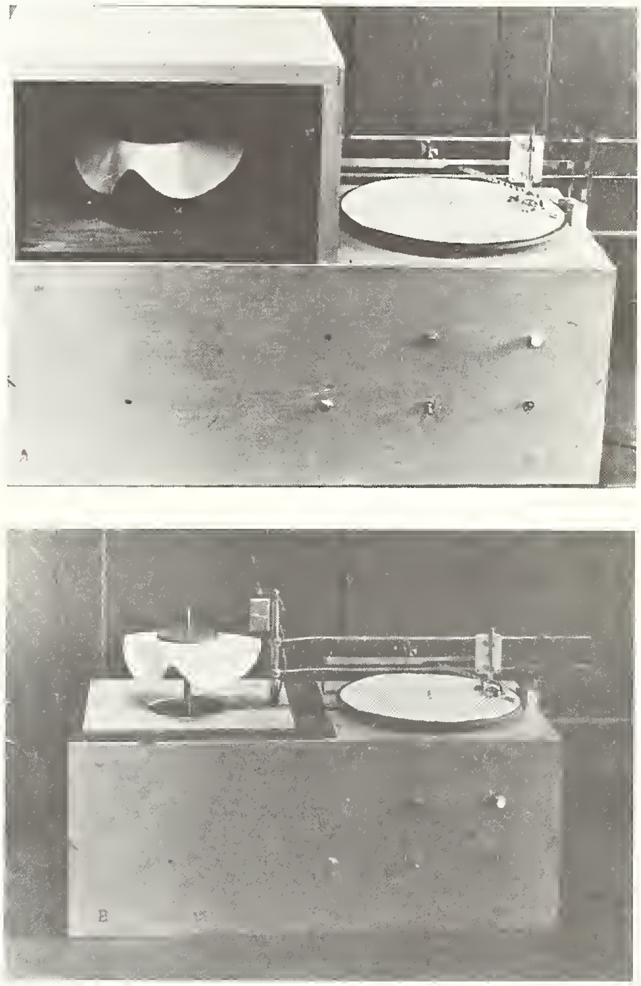


Figure 3.—F.R.L. Drapemeter: **A,** With Hood; **B,** Hood Removed.

3. Amplifier Unit

This unit converts the direct voltage output of the photocell to alternating voltage and amplifies this voltage in order to operate a phase sensitive circuit controlling one phase of the two-phase motor used to position the scanning unit. The amplifier consists of the following parts: an interrupter or chopper which converts the direct voltage to an alternating voltage; an alternating current amplifier; and a phase sensitive output circuit which is connected to one phase of the motor. The amplifier and motor make up a matched unit.

C. Operating Instructions

1. Sample Preparation

The samples used on this machine are 10 inches in diameter, although sizes up to 12 inches may be accommodated. The circle may be drawn on the fabric by means of a compass, with appropriate markings to locate the center. The samples with a quarter inch hole in the center are carefully cut out with scissors, care being taken to avoid distortion or creasing of the fabric.

2. Calibration

The instrument is calibrated as follows:

a. Turn on main switch, allow 10 minutes for the machine to warm up.

b. Place a blank chart on the chart table. Using the sample disk (either 4" or 5") as a guide, trace a circle on the chart.

c. Raise hood, remove sample disk from chart table and place on spindle; replace hood and turn on photocell switch.

d. Set planimeter wheel on circle which was previously traced on chart. This is done by sliding pen carriage along the connecting bars.

e. Press repeat button to begin rotation. After one complete revolution, read off the area from planimeter dial.

f. Compare this value with the actual area of the sample disk.

g. Adjust position of pen carriage and repeat steps (e) and (f) until the area is within 0.10 square inch of the actual value.

3. Test Procedure

a. Depress sample disk and its spindle so that the top surface of the sample disk is flush with the base of tester.

b. Put the sample on the sample disk, care being taken to minimize flexing or distorting the material. The specimen should lie flat and be free of folds and wrinkles.

c. Place a weighted disk of the same size over the sample disk so that the center portion of the sample will be held tight.

d. Raise spindle until the top of the weighted disk is just below the photocell, then begin test by turning on photocell switch and pressing the repeat button.

Note: The photocell switch must be turned off when the hood is raised; otherwise, the unbalance of lighting will cause the photocell to move beyond its normal limits, thereby possibly causing damage.

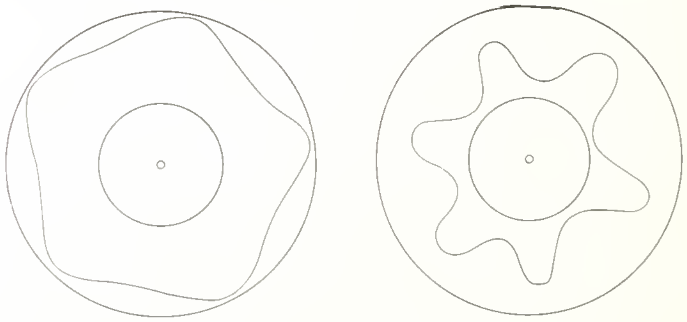
e. The area under the draped sample is obtained by use of the integrator mechanism. (Description of the integrator is given elsewhere in this report.) The area may be read from the integrator dial after one complete revolution of the turntable.

f. Replace the integrator with the pen and rotate the sample again to make a permanent chart.

It is advisable to draw a set of reference circles on the same chart. The reference circles are those drawn with the sample disk and the 10-inch disk. It is true that the area measurement and the drape diagram are not obtained during the same cycle, but tests have shown that the projected area remains virtually unchanged for two or even three cycles. In future models it will be possible to obtain the area measurement and the diagram simultaneously.

4. Calculations

In addition to the calculation of the Drape Coefficient mentioned earlier, other parameters taken from the Drape Diagrams are evaluated. Detailed discussions on this subject are given in Section IV. Typical Drape Diagrams are shown in Figure 4.



Figures 4.—Typical Drape Diagram: **A**, Cotton Fabric No. CF117—Sateen; **B**, Acetate Fabric No. 400A—Plain Weave.

D. Integrator Unit (Figures 5, 6, and 7)

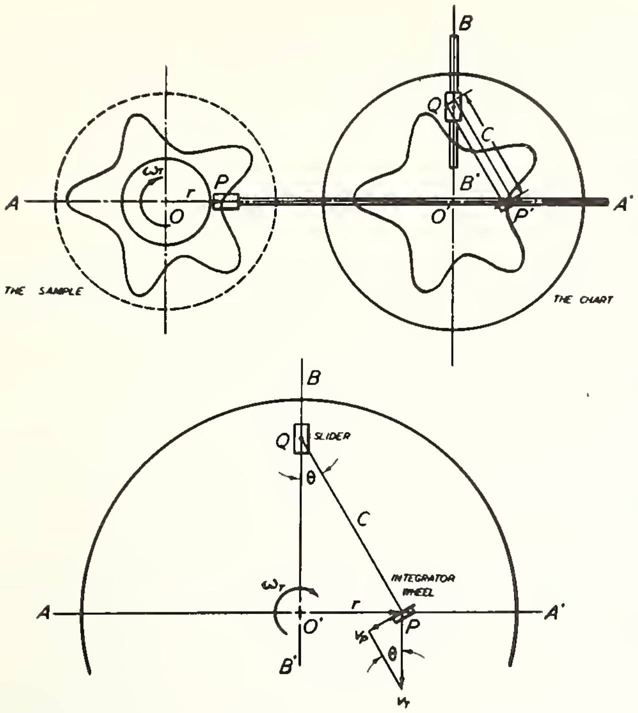


Figure 5.—Integrator.

Since the evaluation of drape by this instrument depends upon the ratio of the projected area to the flat area of the sample, some method of determining the projected area must be used. The chart may be planimetered in the customary fashion but this method is time consuming and its precision limited by operating errors.

For this reason, an integrator unit was developed which could be mounted in place of the pen and which could be used to give the area directly by making one or more rotations of the sample and chart.

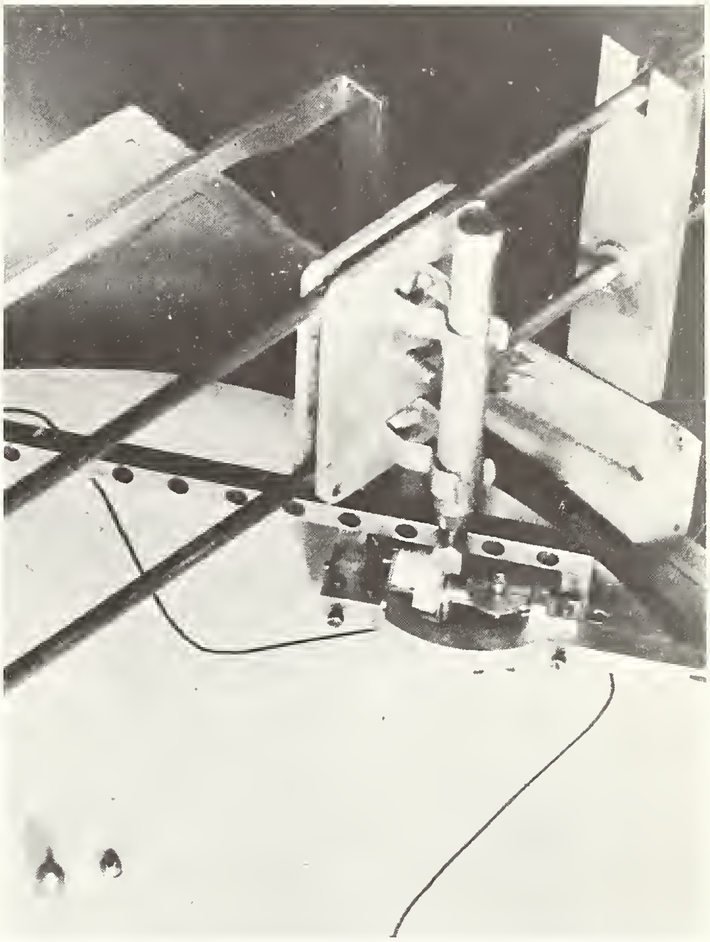


Figure 7.—Integrator (Closeup of Planimeter).

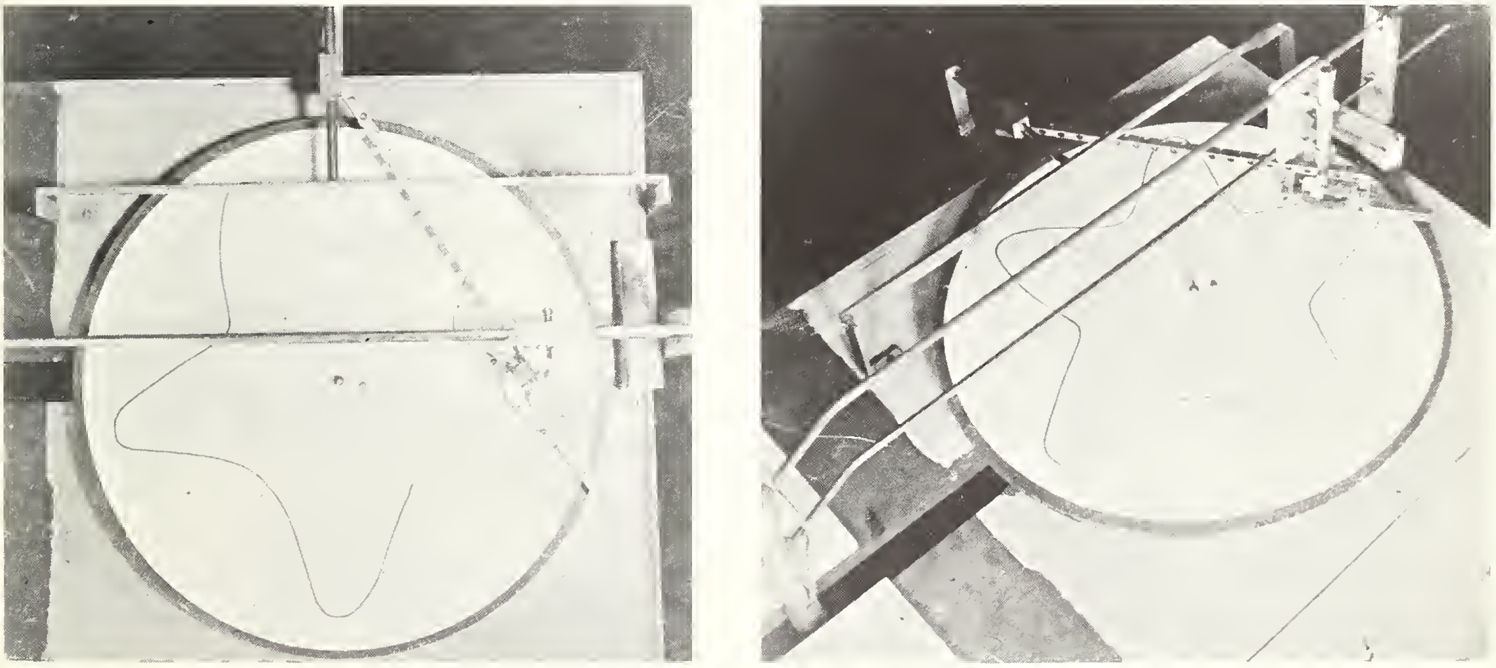


Figure 6.—Integrator.

Nomenclature:

P	Location of light beam on sample.
P'	Point of tangency of integrator wheel.
C	Length of connecting bar from Q(pivot on slider) to P' (Axis of integrator wheel is along C).
Dp	Diameter of planimeter wheel.
ω	Angular velocity of planimeter wheel.
v_w	Tangential velocity of planimeter wheel.
ω_T	Angular velocity of chart table.
v_T	Tangential velocity of chart table at P'.
v_P	Component of v_T perpendicular to axis of planimeter wheel.
r	Distance of P' or P from the center of their respective turntables.
θ	Angle between the connecting bar C and the supporting bar BB'.

If there be zero slip between the planimeter wheel and the chart paper,

$$v_p = v_T \sin\theta \quad \text{--------------------(1)}$$

since:

$$v_w = \frac{D_p\,\omega}{2} \quad \text{-----------------------(2)}$$

and:

$$v_T = r\,\omega_T \quad \text{-----------------------(3)}$$

and at the point of tangency, D', between the planimeter wheel and the chart

$$v_w = v_p \quad \text{----------------------------(4)}$$

then from (2), (3) and (4):

$$\omega = \frac{2v_w}{D_p} = \frac{2v_T}{D_p}\sin\theta = \frac{2r\omega_T}{D_p}\sin\theta \quad \text{---(5)}$$

From the diagram, Figure 5:

$$\sin\theta = \frac{r}{C} \quad \text{------------------------(6)}$$

Substituting (6) into (5):

$$\omega = \frac{2r\omega_T}{D_p}\,\frac{r}{C} = \frac{2\omega_T}{CD_p}\,r^2 \quad \text{-----------(7)}$$

But:

$$\omega_T = \frac{d\theta}{dt} = \text{constant} \quad \text{-----------------(8)}$$

and thus:

$$\omega = \frac{2r^2}{CD_p}\,\frac{d\theta}{dt} \quad \text{-----------------------(9)}$$

Letting the total angle through which the wheel turns be Φ, then:

$$\Phi = \int \omega\,dt = \frac{2}{CD_p}\int r^2\,\frac{d\theta}{dt}\,dt = \frac{2}{CD_p}\int_0^{2\pi} r^2\,d\theta = \frac{4}{CD_p}\int_0^{2\pi}\frac{r^2}{2}\,d\theta \quad \text{----}\quad (10)$$

If the pattern is a circle, then r is constant, and:

$$\Phi = \frac{4}{CD_p}\left(\frac{r^2}{2}\,2\pi\right) = \frac{4}{CD_p}\left(\pi r^2\right) = \frac{4}{CD_p}\ \text{(area of circle)------}\quad (11)$$

Let:

$$\Phi = 2\pi N$$

where N is the number of revolutions of the planimeter wheel —(12); Substituting (12) into (10):

$$N = \frac{2}{\pi\ CD_p}\int_0^{2\pi}\frac{r^2}{2}\,d\theta \quad \text{---------(13)}$$

and $\frac{2}{CD_p}$ is the number of revolutions per unit area.

Thus, $N = \frac{2}{\pi\,CD_p} \times [\text{area}]$, since $\int_0^{2\pi}\frac{r^2}{2}\,d\theta$ is equal to the area for any pattern.

For proper operation of the slider, θ should not exceed about 50° and, therefore, C should be sufficiently greater than the radius of the turntable so that $\sin\theta = \frac{r}{C} = 0.6$.

The diameter of the wheel available from a standard planimeter was:

$$D_p = 0.772$$

If $\frac{2}{\pi CD_p}$ should be about 0.1 rev/unit area for the desired precision, then:

$$\frac{2}{CD_p} = \frac{2}{\pi(0.772)\ C} = 0.1$$

and:

$$C = \frac{20}{\pi(0.772)} = \frac{20}{2.425} = 8.247 \text{ inches}$$

Then:

$$N = 0.1\ (\text{area}) = 0.1\int_0^{2\pi}\frac{r^2}{2}\,d\theta$$

and A = area = 10 N, where N may be read off the planimeter wheel up to 10 revolutions and to 2 decimal places. The maximum reading of the integrator is 10.00 revolutions or 100.00 square inches.

E. Advantages and Limitations

1. A variety of fabrics may be tested.
2. An autographic diagram is produced which may be kept as a record. Several diagrams may be on the same chart for various

time intervals to show the relaxation of a fabric.

3. Mechanically computed area is traced more precisely than can be done even by skilled operators using a hand planimeter.

4. Ease and simplicity of operation; requires no experience in evaluation.

5. Time required per test is small since one revolution in 1 minute produces the diagram, and fabrics may be mounted in about the same time.

6. Accuracy and precision.

Since this is a null operating system, the accuracy of the diagram is equal to the precision of calibration which in turn depends only upon the width of the light beam, which may be kept to a minimum by focusing and by use of a pinpoint light source. As shown below, the precision and accuracy of the integrator is greater than the precision with which a sample may be cut.

7. Reproducibility.

Two patterns were cut from cardboard according to actual drape diagram and were used in place of fabric samples. Table 1 shows the results of 10 repetitive tests, on each cardboard pattern. From the coefficients of variation shown in Table I, it is indicated that over a broad area range, a machine variation of less than 0.5% exists. This is of much lower magnitude than fabric variations.

8. Minimum angle resolvable.

Table 1.—*Reproducibility of F.R.L. Drapemeter Areas*

Test No.	Cardboard Sample 1	Cardboard Sample 2
	Square inches	*Square inches*
1	28.92	50.04
2	28.82	49.96
3	28.96	50.08
4	28.89	50.27
5	28.96	50.03
6	28.85	50.06
7	28.97	50.00
8	28.89	49.99
9	29.00	49.75
10	28.99	49.94
Average	28.925	50.012
S.D.	.061	.041
Coeff. Var. (Pct.)—	0.21	0.08

In the present development model, the minimum angle of resolution is established as that angle which will just allow the scanning unit to move from a small radius to a large radius without the sample striking the photocell support. By effecting a minor change in the photocell carriage, the minimum angle may be reduced to that angle determined by the ratio of the maximum speed of the scanner to the speed of the turntable.

If the velocity of the scanner be equal to v in inches per minute, and the turntable speed be one revolution per minute

$$\text{then } \theta_R = \frac{(1 \text{ rpm})360}{v_s/R}$$

The maximum value of R is 5 inches, then:

$$\theta_R \text{ min} = \frac{360}{v_s/R} = \frac{360}{v_s/5} = \frac{1800}{v_s}$$

As v_s is about 5 inches per second (but may be varied slightly by adjusting the damping), then:

$$\theta_r \text{ min.} = \frac{1800}{5 \text{x} 60} = 6^\circ.$$

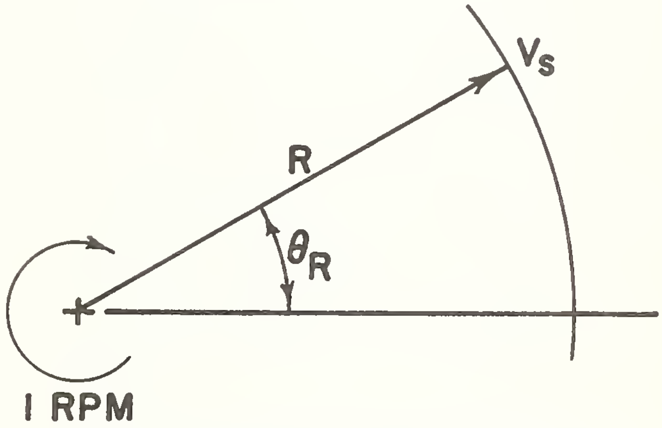


Figure 8.—Minimum Angle of resolution.

In actual practice, any drape sample that might fold so sharply as 6° would also tend to curl under, thus requiring a larger mounting disk. This angle of resolution, therefore, is more than adequate for any practical work.

9. Translucency of fabrics.

This factor becomes important only when the translucency varies across the fabric or when the fabric does not sufficiently alter the light beam. Even for sheer white nylon the machine seems to perform satisfactorily.

10. Accuracy of Calibration and Drift.

By use of a 4-inch disk for calibration, the following results were observed:

Average area	(square inches)	—12.533
S. D.	(square inches)	— 0.048
Coeff. of Var	(percent)	— 0.38
Radius of Disk = 2 ±	(inches)	— 0.002
Area of Disk = 12.566 ±	(square inches)	— 0.025
Percent error = $\frac{0.025}{12.566}$ =	(percent)	— 0.2

The above discussion pertains to the present developmental model only. The means are already known for changing the design to remove most of the limitations mentioned here, also for making the machine more versatile and more sensitive for use as an area-measuring device in its general application.

F. Improved Instrument

The Drapemeter as thus far described herein is the original "breadboard" development model, constructed earlier at F. R. L. Inc.[2]

The improved version of the F. R. L. Drapemeter is shown in Figure 9. This instrument is superior to the first one, described above, incorporating many refinements.

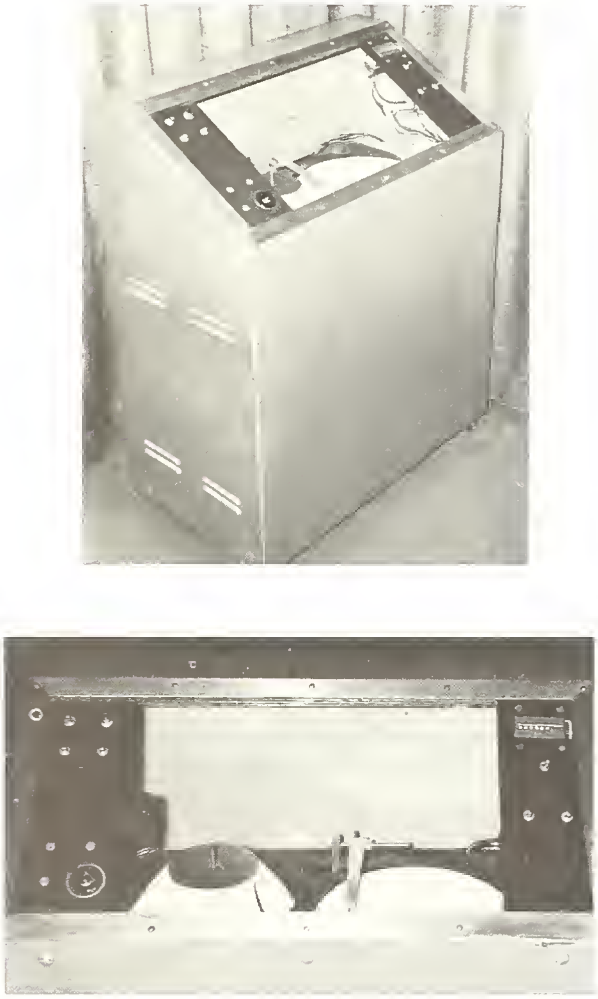


Figure 9.—Improves version of F. R. L. Drapemeter: **A**, full view, **B**, close up.

Some of the major improvements over the previous model are listed below:

1. Optical System

The new instrument employs a single pinpoint light source for both the scanning cell and the comparison cell. The use of the two photo-multiplier tubes is so adjusted that incident light does not affect the measurement, permitting operation of the device without the hood, which was previously required. This will enable the operator to observe the specimen throughout the test.

2. Mechanical Operation

Among the numerous mechanical refinements are the following:

a. The area integration takes place at the same time the drape diagram is drawn.
b. The sample support can be powered or raised semi-automatically.
c. The turntable speed has been reduced from 1 to 0.5 r.p.m., which will decrease the minimum angle of resolution.
d. Limit switches are provided for safety.

3. Integrator Unit

The new integrator utilizes two ball-and-disk-type integrators. The rotation of the output shaft of the second integrator actuates an electrical counter. Thus the area measured can be read directly from a dial.

III. SUBJECTIVE EVALUATION STUDY

A. Introduction

One of the more difficult yet important aspects of any research program is the comparison of laboratory data with service performance. This is especially true of this project, since "drape" is a rather vague description of certain properties in fabrics and, in all probability, most people have their own conceptions as to what is good and poor drape. It was therefore the purpose of this subjective evaluation study to determine the following:

1. What defines "drape" and in particular what are the qualities which make for good drape?
2. How good an instrument is the Drapemeter, i. e., what is the correlation between Drapemeter data and subjective

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[2] Chu, C. C., Cummings, C. L., and Teixeira, N. A., "A Study of Factors Affecting the Drape of Fabrics—The Development of a Drapemeter." Textile Research Journal 20: 539-548, August 1950.

ranking? Which is more sensitive to small differences in drapability?

3. Do fabric experts, who evaluate drape by sight and by hand, agree amongst themselves in ranking fabrics for drapability?

B. Review of Conferences

Interviews were held with groups of people from the fabric trade, selected because of their close relationship with the designing, styling, and merchandising of fabrics. They were asked questions such as:

1. What are the properties in any fabric for which you look when judging its draping quality?
2. Can you rank an assortment of fabrics according to their drapabilities?
3. What are your general opinions regarding this subject?

The following are typical miscellaneous statements concerning their response:

1. Drape should be classified by end-uses such as draperies, curtains, women's wear, and men's wear.
2. Distinction of end-uses should be made. This may mean that the draping quality of a given material may be good for curtains, but poor for a woman's skirts.
3. Distinction should be made between the "drape" of apparel and drapery materials.
4. The criteria for drapability for different end-uses are not the same,
5. Even within the same end-use classification (i. e., whether draperies or apparel) different types of material cannot be evaluated together; viz. knitted jersey vs. chambray.
6. Consumers have fixed conceptions regarding the properties and the end-uses of various fibers.
7. Certain poor draping characteristics are desirable for the sake of fashion or for novelty effects, such as the "crispness" of taffeta and the coarseness of burlap cloth.
8. "Hand" is equally as important as visual evaluation in judging drapability.
9. Drape and "hand" go together.
10. "Hand" cannot be separated from "drape."
11. Drape and "handle" should not be divorced.
12. It is commonly agreed that "handle" goes together with "drape."
13. Crease resistance may be related in some way to drape.
14. Resin treatments on synthetic fibers to improve drape are not so satisfactory as the use of natural fibers.
15. Drape is dictated by fashion.
16. The weight of the fabric, the length of fabric hanging, and the ratio of the two will affect drape.
17. Linings which add weight to apparel or drapery fabrics will usually improve drape.
18. Addition of weight can improve drape.
19. Drape is not defined alone by certain graceful forms, but rather by the material's ability to form such shapes by itself.
20. Problem of drape is not serious in men's wear.
21. Drape is important in men's wear.
22. Cut and tailoring can improve drape more than improvement in the draping qualities of the material.
23. Fabric construction is important in its effect on drape.
24. "Liveliness," which is that property of a fabric enabling it to form into graceful and pleasing folds without being deliberately set, is good drape.
25. Synthetic fibers drape poorly because of their lack of "Liveliness."
26. Cotton fabrics, with the proper construction, can be just as drapable as fabric of other fibers.

The gamut of answers is indicative of the inability of the respondents to agree with each other in their feelings with respect to both drape and hand.

C. Collection of Fabric Samples

Information obtained through the aforementioned conferences was of material aid in a selection of fabrics for evaluation. Forty-eight fabrics, covering virtually all varieties of fiber types, weaves, weights, and end-uses, were purchased. These fabrics were tested on both the Drapemeter and the Strip Bending Tester.[3]

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[3] Description given in section IV -E.

Results of these tests are given in Table 2.[4] Ten out of the 48 fabrics were selected for the subjective evaluation study.

Drape Coefficients of the 48 fabrics ranged from 24.9% (when $\beta = 0.5$) for fabric No. 47, the most drapable sample, to 88.9% for fabric No. 19, the least drapable. Theoretically, it is possible that as the Coefficient is lowered, a point would be reached where poor drape would result owing to excessive limpness of the fabric. This point was not reached in this study and as yet the full significance of the possibility has not been explored. The fabrics chosen for the subjective evaluation study included the two extremes and eight intermediate samples with an average incremental difference of roughly 7% in their F. R. L. Drape Coefficients. A 7% difference in Drape Coefficient is more than adequate to insure real differences between the fabrics studied. For example, it can be calculated that during the test 7% difference in the Drape Coefficient is equivalent to a difference of 4.20 square inches of area (when $\beta = 0.5$) measured by the Drapemeter. Actually, it has been conclusively shown, at least for the variability evidenced by all fabrics studied to date, that a 2% difference in Drape Coefficient (1.20 square inches of area, $\beta = 0.5$) is a significant difference. Further, it has been shown that the Drapemeter areas for any given fabric specimen are reproduced within ± 0.20 square inches, thus providing an accuracy which permits full confidence that the 7% differences in Drape Coefficient shown in Table 3 were adequate for this study. Even though the bending tests rated the fabrics chosen for subjective evaluation in the same order as the Drapemeter did the data of Table 4 show that the variability in the results is much greater for the strip bending test than for the F. R. L. Drapemeter. This is an important factor to be considered in judging the

Table 2.—*Drape Coefficients and Bending Lengths of Miscellaneous Fabrics*

Fabric No.	Type of Material	Drape Coefficient, F	Bending Length, C
		Percent	*Inches*
1	100% Worsted suiting	44.3	0.58
2	100% Worsted suiting	42.0	.55
3	100% Worsted suiting	42.6	.57
4	100% Worsted suiting	42.0	.57
5	100% Worsted suiting	41.8	.57
6	100% Worsted suiting	41.7	.56
7	100% Worsted suiting	44.7	.60
8	100% Worsted suiting	45.2	.61
9	100% Worsted suiting	49.8	.62
10	86%—14% Mohair women's suiting	45.3	.66
11	86% mfg. fiber—14% Mohair women's suiting	46.6	.65
12	46% Cotton—54% rayon damask drapery fabric	73.1	1.20
13	100% Cotton damask drapery fabric	74.1	1.14
14	100% Cotton brocade drapery fabric	78.0	1.39
15	100% Cotton damask drapery fabric	72.1	1.12
16	100% Silk damask drapery fabric	42.7	.93
17	Silk damask drapery fabric	58.6	1.32
18	100% Nylon marquisette	[1]	....
19	100% Rayon brocade drapery fabric	88.9	1.57
20	44% Cotton—56% rayon damask drapery fabric	86.2	1.37
21	100% Nylon ripstop parachute cloth	39.4	.66
22	67% Cotton—33% rayon upholstery fabric	63.8	.87
23	100% Cotton velveteen pile fabric	46.8	.63
24	33% Cotton—67% rayon drapery fabric	47.0	.74
25	17% Cotton—83% mfg. fiber upholstery fabric	41.2	.75
26	72% Mohair—28% mfg. fiber "Springweave" worsted suiting	51.5	.71
27	75% Mohair—25% rayon worsted suiting	48.1	.72
28	42% Mohair—58% mfg. fiber "Sunfrost" worsted suiting	46.6	.67
29	Burlap	[1]	--------
30	31% Rayon—43% cotton—11% Mohair—15% metal drapery fabric	76.4	1.05
31	71% Cotton—29% mohair drapery fabric	62.4	.82
32	38% Rayon—49% cotton—13% mohair drapery fabric	60.7	.81
33	69% Cotton—31% mohair curtain fabric	46.8	.83
34	12% Rayon—50% cotton—38% mohair drapery fabric	57.9	.86
35	Continuous filament blouse fabric	26.7	55
36	Spun dress goods	31.5	.62
37	Spun dress goods	29.1	.57
38	Spun dress goods	34.7	.62
39	Continuous filament blouse fabric	33.3	.57
40	Rayon satin blouse fabric	66.9	1.23
41	Rayon gabardine sportswear	46.8	.67
42	Rayon gabardine sportswear	46.0	.67
43	Rayon gabardine sportswear	38.3	.67
44	Rayon gabardine sportswear	37.3	.57
45	Continuous filament dress goods	48.6	.67
46	Rayon gabardine sportswear	31.6	.58
47	Crepe dress goods	24.9	.48
48	Crepe dress goods	25.6	.53

[1] Sample cannot be evaluated because of openness

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[4] Each Drape Coefficient recorded was averaged from six tests, three each from the face and the back of the fabric. Samples were 10 inches in diameter and were tested at $\beta = 0.50$; i.e., the ratio between the diameter of the support and that of the sample is $5''/10'' = 0.50$.

Table 3.—*Objective Ranking of Fabric Used in Subjective Evaluation Tests*

Fabric No.	Description	F.R.L. Drapemeter Ranking	F@ = 0.5	c_s
			Percent	*Inches*
47	Rayon crepe	1 (best)	24.9	0.48
46	Rayon gabardine	2	31.6	.58
23	Cotton velveteen	3[1]	46.8	.63
28	Blended suiting	4[1]	46.6	.67
26	Blended suiting	5	51.5	.71
34	Blended drapery fabric	6	57.9	.86
22	Blended upholstery fabric	7	63.8	.87
15	Cotton damask	8	72.1	1.12
14	Cotton brocade	9	78.0	1.39
19	Rayon brocade	10 (poorest)	88.9	1.57

[1] In the statistical analyses (Table 8), fabric No. 23 was treated in 1 case as 3rd and in 1 case as 4th place in the ranking, in order to calculate the difference in ranking it both ways by subjects.

value of these two tests as means of measuring drape. For example, it may be noted in Table 8 that a somewhat better correlation exists between the strip bending test data and the subjective evaluation of stiffness than exists between Drapemeter data and the subjective evaluation of gracefulness. Apart from all other considerations (including the relation of drape and stiffness), the large variability in strip bending data would make for less reliable predictions than would be possible by the use of Drapemeter data.

Table 4.—*Statistical Analysis of Objective Ranking of Fabrics Used in Subjective Evaluation Test*

Fabric No.	Drapemeter Test[1]			Strip Bending Test[2]		
	F	Coef. of Variation	Sig.[3]	c_s	Coef. of Variation	Sig.[3]
	Percent	*Percent*		*Inches*	*Percent*	
47	24.9	1.69	yes	0.48	4.68	yes
46	31.6	1.81	yes	.58	4.47	yes
23	46.8	3.52	no	.63	7.72	yes
28	46.6	2.04	yes	.67	3.61	yes
26	51.5	1.56	yes	.71	3.25	yes
34	57.9	1.69	yes	.84	17.64	no
22	63.8	1.99	yes	.87	9.10	yes
15	72.1	5.35	yes	1.12	8.73	yes
14	78.0	7.44	yes	1.39	25.78	no
19	88.9	1.33	------	1.57	25.54	------

[1] Averaged from 18 values.
[2] Averaged from 40 values.
[3] "Sig." refers to question of statistically significant difference in ranking of a fabric in drape quality as compared to the fabric listed immediately below.

The samples for subjective evaluation were cut to 30 by 48 inches in size, the 48-inch dimension being in the warp direction. This size of specimen was decided from the conclusions derived from a series of interviews with various people in the trade, who stated that such a size was necessary as a minimum for evaluation. The specimens were carefully pressed and packed in a specially constructed carrying case so that they might be kept in an unwrinkled condition. All respondents evaluated the same pieces of fabric.

Inadvertently, an error was made in the selection of the ten fabrics for field study, whereby two of the fabrics, Nos. 23 and 28, had different strip bending lengths but statistically identical Drape Coefficients. This mistake in no way mitigated against the value of the study and actually provided the basis for some useful speculation, as noted in the later discussion of Table 6, which summarizes all of the gracefulness rankings and compares them to the rankings given by the Drapemeter.

D. Polling Method.

Sixty-six subjects participated in the study, but only 57 persons filled out their questionnaires completely. The remaining nine were unable to rank the fabrics other than to select the extremes.

The subjects were grouped as follows:

1. Chemical laboratory personnel at the Mellon Institute, Pittsburgh, Pa.
2. College teachers of textiles.
3. Employees and customers solicited in the yard goods section of a large department store in Boston.
4. Interior decorators doing business in Boston.

In addition to a verbal explanation as to the object of the experiment, and necessary instructions governing procedure (in particular, to rank the fabrics without specific end uses in mind), the subjects were given a printed questionnaire form, reproduced below:

> This experiment is devised to check consumer evaluation of certain fabric properties against our laboratory test results. Please examine the samples carefully and list your ranking according to the following:
>
> Stiffness: By visual observation and handling, rank the stiffness of these fabrics from the most limp to the most stiff.
>
> Gracefulness of folds: When the fabrics are in a hanging position, rank them for the pleasingness or gracefulness of the folds or pleats.

Name .... Occupation ....

Stiffness Ranking

Most Limp Fabric	2nd	3rd	4th	5th	6th	7th	9th	Most Stiff

Gracefulness Ranking

Most Graceful Fabric	2nd	3rd	4th	5th	6th	7th	9th	Least Graceful

Please also indicate the fabric you like best........

Why? ....

E. Results of the Study

1. Group Analyses

The average rankings given by all the subjects, subdivided into groups surveyed, are shown in Tables 5 and 6.

Table 5.—*Subjective Evaluation: Stiffness Rankings*

Fabric No.	47	46	23	28	26	34	22	15	14	19
Strip bending ranking	1	2	3	4	5	6	7	8	9	10
Chem. lab. personnel	1	2	5	6	4	3	8	7	9	10
Textile teachers	1	2	6	3	4	5	8	7	9	10
Dept. store personnel	1	2	6	4	3	5	8	7	9	10
Interior decorators	1	2	3	4	6	5	8	7	9	10
All subjects	1	2	6	3	4	5	8	7	9	10

Table 6.—*Subjective Evaluation: Gracefulness Rankings*

Fabric No.	47	46	23	28	26	34	22	15	14	19
Drapemeter ranking	1	2	3	4	5	6	7	8	9	10
Chem. lab. personnel	6	4	1	3	2	5	7	8	9	10
Textile teachers	1	2	3	4	5	7	9	6	8	10
Dept. store personnel	3	2	1	5	4	6	8	7	9	10
Interior decorators	2	3	1	4	7	6	9	5	8	10
All subjects	4	2	1	3	5	6	8	7	9	10

Examination of Tables 5 and 6 indicates that there seems to be somewhat better agreement between Subjective Evaluation of Stiffness and Strip Bending Test Rankings than there is between Subjective Evaluations of Gracefullness and Drapemeter Rankings. Quantitative comparisons are given in Table 8, and possible reasons are also discussed.

The essence of Table 6 may be rearranged as follows:

Fabric No.	Drapemeter Ranking	Rankings (All Respondents) Av. Subjective
47	1st (Best)	4th best
46	2d	2d best
23	3d	1st (Best)
28	4th	3d best
26	5th	5th best
34	6th	6th best
22	7th	8th best
15	8th	7th best
14	9th	9th best
19	10th (Worst	10th (Worst)

It is obvious that the subjects and the Drapemeter are not in perfect agreement, but the agreement is very good in light of the general experience in attempting to compare instrument and field data in textile evaluation studies.

Several speculative comments relative to Table 6 might be made at this point.

First, it may be observed that the major discrepancies between the rankings of the evaluators in general and those of the Drapemeter are concentrated among the *best* four fabrics. One might expect that as respondents proceed in choosing between good and poorer draping quality, progressively greater difficulty in making rational discrimination must have been imposed upon them as they attempted to select the better fabrics, since of course they all knew that only one could have a ranking of "best." Therefore, as the psychological tension built up, it would be natural for respondents to be influenced by more and more factors than "pure" gracefulness in making a ranking. Such a condition seems apparent in the case of fabrics No. 23 and No. 28, which the Drapemeter ranked similarly. No. 23 was a cotton velveteen, heavy, soft, and with a tradition of luxury in the decorative field. No. 28 was a crisp, light suiting of mohair and rayon. It is difficult to imagine many individuals who, faced with the necessity of making a fine judgment concerning gracefulness and yet *being able to handle these two fabrics,* as was the case in this study, would fail to rank No. 23 better than No. 28. It is significant to note from Table 6 that only the teachers appeared able to exercise the necessary intellectual discipline to effect a perfect correlation with the Drapemeter in ranking the four best fabrics. Of all the groups in the study, one might have anticipated that the teachers alone, by training and by professional activity, could most closely approximate a completely dispassionate point of view.

In the light of this argument, therefore, the shifts in subjective evaluation of the four best fabrics, shown in Table 6, are normal and inevitable when, dealing with a complex, subjective, variable, like drape, and a complex, subjective variable, like people. Therefore, the fact that the correlation coefficient between subjects and Drapemeter was roughly 0.8 (see Table 8) is a remarkable validation of the Drapemeter. In most biological research, of which this field study is a special case, correlation coefficients of 0.5 are considered sufficiently good to form a basis for continuing research. It is to be doubted that the psychological interference briefly described above can ever be removed from a study of drape. Therefore, the evidence was positive and conclusive that the Drapemeter will and should be used from this point on to study drape in purely physical terms.

Second, it may be observed that the fabric ranked best (lowest Drape Coefficient) by the Drapemeter was ranked fourth best, on the average, by all subjects. Even though the average rank of fourth is distorted by the rank of sixth assigned by the chemistry laboratory personnel, the shift is worthy of comment.

It was noted earlier in this report that a problem exists in the use of the Drapemeter in that as the Drape Coefficient is lowered it is considered possible to reach a point where the instrument is measuring limpness, which for the practical purposes of this research is a negative property, e. g., one that would detract from drape if predominant. The point at which a low Drape Coefficient changes from a measure of superior drapability to a measure of excessive limpness has not been determined for any fabric. As a result of the shift noted in the paragraph above, however, one might speculate that fabric No. 47, a rayon crepe with a Drape Coefficient of 24.9% F @ $\beta = 0.5$, is fringing on the borderline. Examination of the 10 swatches included in this report revealed that this crepe is undoubtedly the limpest of all samples studied in the field and it *may* be for this reason that many respondents failed to rank the crepe similarly to the Drapemeter. The question of the lowest limits of Drapemeter Coefficient usefulness is worthy of further analysis. Noting the existence of the problem does not imply that the research into the physical aspects of drape, using fabrics whose Drape Coefficient are in a safe range, should have been delayed.

To fully interpret the significance of these subjective and objective evaluation comparisons; several statistical analyses have been made, as follows:

a. A check on the agreement among the subjects, within each group and within the entire population of subjects (Table 7).

b. A check on the agreement between subjective and instrument rankings (Table 8), under the following conditions:
   i. When fabrics Nos. 23 and 28 are ranked in 3d and 4th places, respectively (Table 8,B).
   ii. When fabrics Nos. 23 and 28 are ranked in 4th and 3d places, respectively (Table 8,C), thus reversing the order of b-i above.

Table 7.—*Statistical Analysis of Subjective Evaluations Among the Subjects Themselves*

Ranking and Subject	Concordance Coefficient [1]	Significance [1]
A. **Stiffness Rankings:**		
1. Chemistry laboratory personnel	0.821	Alike
2. Textile teachers	.959	Alike
3. Department store personnel	.888	Alike
4. Interior decorators	.794	Alike
5. All subjects	.829	Alike
B. **Gracefulness Rankings:**		
1. Chemistry laboratory personnel	0.533	Alike
2. Textile teachers	.699	Alike
3. Department store personnel	.319	Alike
4. Interior decorators	.384	Alike
5. All subjects	.333	Alike

Sample calculations are given in the Appendix.

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[1] See literature reference by Winn and Schwarz noted in the Appendix for the use of Concordance Coefficient and explanation of "z" test. The significance is determined by "z" test.

Table 8.—*Statistical Analysis of Subjective Evaluations Between the Subjects and the Instrument Rankings*

Test and Subject	Correlation Coefficient	Significance
A. **Strip Bending Test:**		
1. Chemistry laboratory personnel	0.733	Alike
2. Textile teachers	.822	Alike
3. Department store personnel	.778	Alike
4. Interior decorators	.911	Alike
5. All subjects	.822	Alike
B. **Drapemeter (ranking no. 23 at 3d place):**		
1. Chemistry laboratory personnel	.600	Alike
2. Textile teachers	.867	Alike
3. Department store personnel	.778	Alike
4. Interior decorators	.689	Alike
5. All subjects	.778	Alike
C. **Drapemeter (ranking no. 23 at 4th place):**		
1. Chemistry laboratory personnel	.556	Alike
2. Textile teachers	.822	Alike
3. Department store personnel	.733	Alike
4. Interior decorators	.644	Alike
5. All subjects	.733	Alike

2. General Comments

In general, the subjects were quite cooperative; their reactions usually fell into one of three principal categories. However, it is difficult to define exactly to which category many of the participants might rightfully belong. The three categories, cited below, are examples of extreme cases where little doubt exists as to proper grouping.

a. Some of the subjects were readily able to grasp the objectives of the test. Most of these could visualize the concept of ranking for gracefulness without regard for the end-use of the material. *Examples of their rankings of gracefulness are shown below*:

Drapemeter Ranking	1	2	3	4	5	6	7	8	9	10
Anonymous Ranking	1	2	6	3	4	5	7	8	9	10
R. G. Ranking	1	2	6	3	4	5	8	7	9	10
J. G. Ranking	1	2	6	3	4	5	9	7	8	10
O. G. Ranking	1	2	6	4	3	5	8	7	9	10
A. R. D. Ranking	1	2	4	3	5	6	7	8	9	10
B. S. Ranking	1	3	2	4	5	6	7	8	9	10
D. W. W. Ranking	1	2	6	4	7	3	10	5	8	9
A. E. H. Ranking	1	2	4	8	9	10	5	3	6	7
N. D. C. Ranking	1	2	3	4	5	6	7	9	10	8

The Drapemeter rankings are from 1 (the most drapable) to 10 (the least drapable). Consider the rankings of R. G. for example: the respondent agreed with the Drapemeter in ranking fabrics No. 47 and No. 46 in the 1st (best) and 2d places, respectively. However, his choice for the third best was fabric No. 34 (ranked 6th by the Drapemeter), etc. Within the above group the correlation between the Drapemeter rankings and the subjective rankings was high.

It is interesting to note that a few members of this group indicated in subsequent discussion that the gracefulness and stiffness ranking *had* to be identical.

b. The second group maintained that it is impossible to "compare apples with oranges," i. e., to compare fabrics of different types or fabrics intended for different end uses.[5] Of a consequence, they ranked the fabrics with a specific end-use in mind. This attitude resulted in two types of reversals:

i. Those who ranked each fabric in terms of drapery use, thus placing the stiffer fabrics near the top of the list. Examples of such compromises are the gracefulness rankings of K. C. A., E. H., and F. C. W.

Drapemeter Ranking	1	2	3	4	5	6	7	8	9	10
K. C. A. Ranking	10	9	1	6	8	7	2	3	5	4
E. H. Ranking	10	9	3	5	6	4	7	2	8	1
F. C. W. Ranking	10	9	3	1	2	4	5	7	6	8

ii. Those who ranked each fabric in terms of appeal use (skirts and capes, etc.), whereby the more flexible samples were placed near the middle while the leading fabrics were those which exhibited medium stiffness. This group represented a sizeable portion of the population (perhaps as much as 40%, although, as was previously mentioned, not all members of the population could be classified with equal ease and certainty). Their rankings are typified by the following:

Drapemeter Ranking	1	2	3	4	5	6	7	8	9	10
D. M. J. Ranking	5	6	1	2	4	3	8	7	10	9
K. H. Ranking	7	2	1	3	4	5	6	8	9	10
E. K. Ranking	3	7	4	2	1	9	6	5	8	10
R. S. W. Ranking	3	4	2	5	1	6	8	7	9	10

c. Lastly, a group of heterogeneous subjects who for some reason gave rankings with virtually no correlation whatsoever. Among those were a few interior decorators who professed that "drape" had never been any problem to them.

Drapemeter Ranking	1	2	3	4	5	6	7	8	9	10
Anonymous Ranking	6	4	1	8	3	9	2	7	10	5
H. E. K. Ranking	10	5	2	7	9	6	8	1	4	3
R. B. Ranking	3	8	1	7	9	4	2	5	6	10
J. C. Z. Ranking	3	10	1	6	7	8	2	4	5	9
A. N. B. Ranking	7	6	1	5	3	2	10	4	8	9

F. Conclusions

1. It has been shown that "drape" is a meaningful term. The fact that the respondents in the subjective test agreed among themselves indicates that they must have ranked the fabrics against some measurable standard, approximately common throughout their experiences.

2. The F. R. L. Drapemeter has been proven capable of measuring drape, since the agreements between subjective and instrument rankings were statistically highly significant. The Drapemeter is capable of detecting significant differences in Drape Coefficients as small as 2%, with results that are highly reproducible.

3. The strip bending tester, on the other hand, while it may be a reliable instrument for measuring stiffness, is not adequate for measuring drape. Previous work has shown that the monoplanar deformation of a strip test has many shortcomings as compared with the multiplanar deformations incurred in the Drapemeter tests. The research herein reported further validates this thesis.

The success in validating the F. R. L. Drapemeter represents a significant contribution to the solution of the ultimate problem defined by this project, namely, to determine the structural factors influencing the draping properties of cotton fabrics. It will be recollected that at the time this research was initiated, no instrument was in use that by means of a simple physical measurement could classify the drapability of a fabric in such a way as to correlate with expert trade opinion. This meant that, lacking such an instrument, research to the end of differentiating the factors contributing to drape was not practical. Every set collected of controlled fabrics would first have required extensive field evaluations which at best are time consuming, difficult to control, and costly. It is concluded that the subjective property "drape" can now be confidently machine measured as effectively as by extensive, statistically controlled opinion polls in the field.

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[5] The attitude mentioned at this point was defined partially by discussing the problem with several respondents, and partially by extrapolating from the rankings obtained and from the knowledge of the respondent's professional activity.

IV. MECHANISM OF DRAPE

This section will be devoted to a discussion of some of the preliminary attempts to investigate the mechanics of fabric drape from an analytical point of view. These studies are based on the classical principles of applied mechanics on beam and plate deflections, simplified and modified for the particular problems concerned.

A. Deflection Analyses of Draped Samples

1. Application of Flat Plate Theory

The stresses involved in a draped sample are small; there are no externally exerted loads on the sample other than the sample's own weight, which is uniformly distributed over the entire overhanging area. The following is an analysis of the drape sample using the flat plate as a model, and flat plate theory for calculations.

R. J. Roark[6] has listed for a circular plate, supported in the center and uniformly loaded as shown in Figure 11, the following equation for the edge deflection, y. Poissons' ratio is assumed to be zero.

$$y = \frac{3w}{16Et^3}\left[\frac{7a^6+b^6-a^4b^2-7a^2b^4-4a^2b^2(5a^2+b^2)\ln\frac{a}{b}-16a^4b^2(\ln\frac{a}{b})2}{a^2+b^2}\right] \text{------}(15)$$

where:

w = Weight of fabric per unit area.
E = Modulus of elasticity.
t = Thickness of fabric
a = Radius of sample.
b = Radius of sample disk.

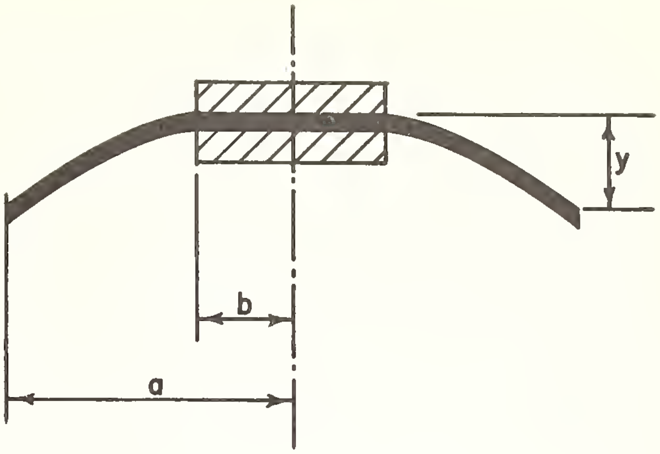

Figure 10.—Diagram of a draped sample.

Simplifying (15) and letting $\beta = b/a$ there results:

$$y = \frac{3wa^4}{16Et^3}\left[\frac{7+\beta^6-7\beta^4-\beta^2+4\beta^2(5+\beta^2)\ln\beta-16\beta^2(\ln\beta)^2}{1+\beta^2}\right] \text{----------} (16)$$

Further simplification results in the following:

$$y = \frac{\alpha wa^4}{Et^3} \text{----------------------} (17).$$

Values of (α) corresponding to a range of values of Beta shown in Table 9.

Table 9.—*Deflection Coefficient, α of Flat Plates*[1]

Beta β	Alpha α
0.0	Infinite
.1	1.054
.2	.720
.3	440
.4	.241
.5	.115
.6	.046
.7	.014
.8	.003
.9	--------
1.0	.000

[1] Edge deflection of circular plate, $y = \frac{\alpha wa^4}{Et^3}$ where

$$\alpha = \frac{3}{16}\left\{\frac{7+\beta^6-7\beta^4-\beta^2+4\beta^2(5+\beta^2)\ln\beta-16\beta^2(\ln\beta^2)}{1+\beta^2}\right\}.$$

The deflection of a circular flat plate can be represented schematically by Figure 11. For the dimensions: (a-b) is the length of overhang; y is the vertical edge deflection and (x-b)

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[6] Roark, R. J., "Formulas for Stress and Strain," 2d Ed., McGraw-Hill Book Company, Inc., 1943.

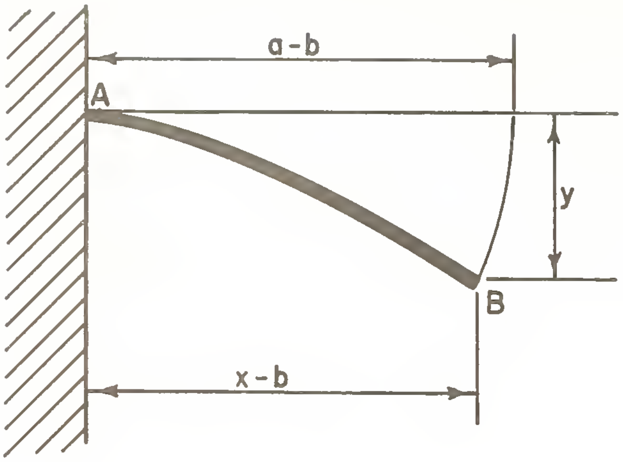

Figure 11.—Deflected plate.

is the horizontal projection of the deflected plate. Since the exact deflection curve AB, is not known, let it be assumed for the sake of simplicity as a straight line for an initial trial. AB, of course, is the same length as (a-b) since the stresses are so small that stretching can be neglected. From the assumption made:

$$(x-b) = \sqrt{(a-b)^2 - y^2} \text{ ----------- } (18)$$

From (17) let:

$$y = k a^4 \text{ ---------------------- } (19)$$

where:

$$k = aw/Et^3 \text{ --------------------- } (20)$$

also:

$$k = a/12c^3 \text{ --------------------- } (21)$$

in which c = the "bending length", defined by F. T. Peirce 7/ as:

$$c = (EI/w)^{1/3} = (Et^3/12w)^{1/3} \text{ ------- } (22)$$

substituting (19) into (18):

$$(x-b) = \sqrt{(a-b)^2 - k^2a^8} \text{ ------------ } (23)$$

Simplifying (23):

$$(x-b) = a\sqrt{(1-\beta)^2 - k^2a^6} \text{ --------- } (24)$$

Let: $K = \sqrt{(1-\beta)^2 - k^2a^6}$

Then:

$$(x-b) = a K;\ x = b + a K \text{ ----------- } (25)$$

Figure 12 shows a drape diagram in which the mean radius of the outline is equal to x. The Drape Coefficient, F, is defined as the ratio of projected area over the annular area:

Thus:

$$F = \frac{\pi\left[x^2 - b^2\right]}{\pi\left[a^2 - b^2\right]} \text{ ------------------ } (26)$$

or:

$$F = \frac{x^2 - b^2}{a^2 - b^2} \text{ ----------------------- } (27)$$

Substitute (25) into (27)

$$F = \frac{(b + aK)^2 - b^2}{a^2 - b^2} = \frac{K^2 + 2\beta K}{1 - \beta^2} \text{ ------- } (28)$$

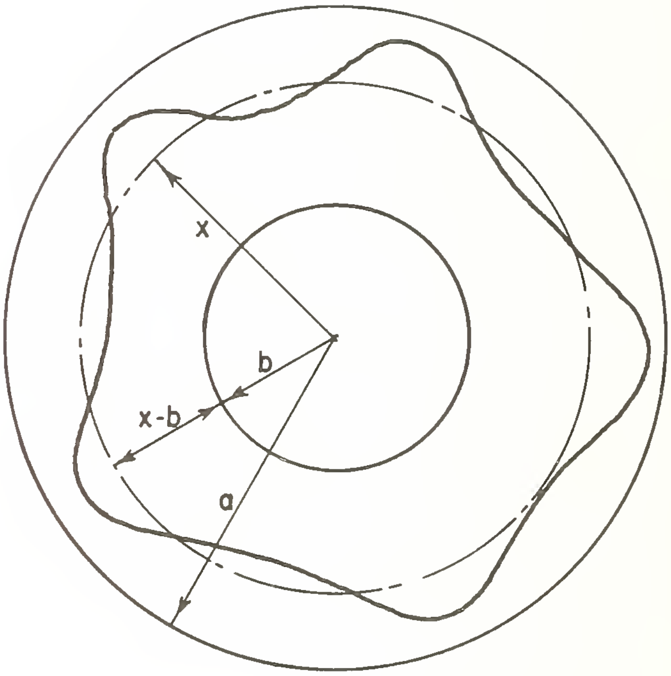

Figure 12.—Components of a drape.

If the physical properties of the fabric are known, then one can calculate the theoretical Drape Coefficient F, by the use of Equation (28). Conversely, if the Drape Coefficient be determined by experiment, then it becomes possible to check the elastic properties, such as the

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[7] Peirce, F. T., "The Handle of Cloth as a Measurable Quantity," Journal of the Textile Institute 21: T377-T416, September 1930.

bending length, c. The bending length thus calculated is called the effective bending length. The obvious steps of such calculation are as follows:

Equation (27) $F=\frac{x^2-b^2}{a^2-b^2}$ $$x=\sqrt{b^2+(a^2-b^2)F} \quad \text{-------------}(29)$$

Equation (23) $(x-b)=\sqrt{(a-b)^2-k^2a^8}$ $$k=\sqrt{\frac{(a-b)^2-(x-b)^2}{a^4}} \quad \text{-------------}(30)$$

Equation (21) $k=\frac{\alpha}{12c^3}$ $$c=\left[\frac{(\alpha)}{(12k)}\right]^{1/3} \quad \text{-----------------}(31)$$

The values of the effective length, c_e, for any value of the Drape Coefficient, F, of a 10 inch sample with $\beta = 0.4$, are given in Table 10.

Unfortunately, this method of obtaining the effective bending length is very unsatisfactory because:

a. The value of c_e is not equal to zero at $F = 0$.

b. Values of c_e for most values of F vary between 1.6 to 2.2 inches; therefore c_e is very insensitive to F and hence undesirable.

Table 10.—*Effective Bending Length, c_e, for 10 Inch Sample when $\beta = 0.4$ [Flat Plate Theory, $\alpha = 0.241$]*

Drape Coefficient, % F	Mean Radius, X	Bending Length, c_e
	Inches	*Inches*
0	2.000	1.611
10	2.470	1.618
20	2.864	1.635
30	3.209	1.660
40	3.521	1.693
50	3.808	1.737
60	4.074	1.796
70	4.324	1.878
80	4.561	2.003
90	4.785	2.241
100	5.000	infinite

A discussion of the sources of error in the foregoing development is given below:

The physical setup of the Drapemeter tests resembles perfectly the classical problem of a circular plate rigidly supported over a central circular area. Hence, the mathematical formula (15), representing the solution to this problem should then be applicable to the test. However, the assumptions underlying the derivation of the formula must be considered. Some of these are:

a. The material is homogeneous and isotropic.

b. The problem is one of linear elasticity, i. e., all strains are linearly functional with the corresponding stresses.

c. The deflection of the plate is small compared to its thickness.

d. All deformations of the circular plate are rotationally symmetric.

It is clear that none of the above assumptions is necessarily true for the case of a fabric. While a reasonable degree of homogeneity can be assumed, isotropy and Hookean linearity can definitely be questioned. For such flexible materials as fabrics, the bending deflections cannot be considered small. With large deflections, circumferential buckling must occur, and produce a wavy form to the edge of the fabric; hence, continuous rotational symmetry cannot exist.

Another error resides in the assumption that the deflection curve is a straight line. It was assumed so merely for the sake of convenience. The actual deflection curve is of an extremely complex form.

It is apparent that good correlations could not have been expected between Drapemeter results and flat plate theory. However, the relevance of the flat plate to the Drapemeter sample clearly exists. It remains for future work to refine the analysis of the flat plate theory to the point where lack of isotropy and existence of large deflections can be properly evaluated and taken into account.

2. Series Approximation of the Curvature of a Cantilever Beam with Large Deflection.

The foregoing analysis treated the deflection curve of a cantilevered circular plate as a straight line, and it was shown that this assumption does not provide a workable solution. The derivation below assumes that the deflection curve may be expressed by a series. The purpose of this study is to express the Drape Coefficient, F, and the effective bending length, c_e, in terms of the projected mean radius $(b+\ell)$.

Consider a cantilever beam of unit width and length, L, carrying a uniform load of w (Figure 13). The general expression for the

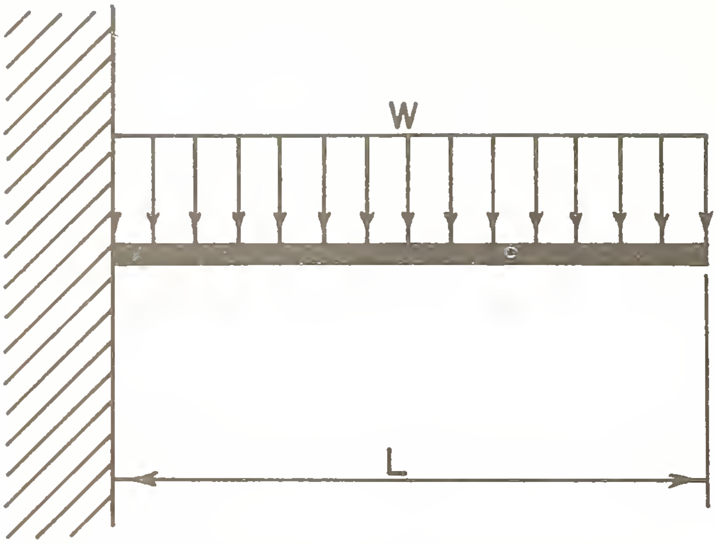

Figure 13.—Beam with large deflections.

bending moment and deflections in such a configuration is as follows:

$$M = \frac{-wx^2}{2} = \frac{EI\,\frac{d^2y}{dx^2}}{\left[1+\left(\frac{dy}{dx}\right)^2\right]^{3/2}} \quad \text{-----------}(32)$$

where all terms have the same meanings previously given, x is the distance to any point on the beam measured from the free end, y(x) is the deflection curve, and M is the bending moment.

Let:

$$p = \frac{dy}{dx} \text{ and } k_1 = \frac{w}{2EI} \quad \text{-----}(33) \text{ and } (34)$$

Substiture (33) and (34) into (32):

$$k_1 x^2 = \frac{dp}{dx\,(1+p^2)^{3/2}} \quad \text{--------------}(35)$$

or:

$$-k_1\int_x^{\ell} x^2\,dx = \int_P^{0} \frac{dp}{(1+p^2)^{3/2}} \quad \text{--------}(36)$$

Integrating (36):

$$\frac{k_1}{3}\left(\ell^3 - x^3\right) = \frac{p}{(1+p^2)^{1/2}} \quad \text{--------}(37)$$

Solving (37) $1 + p^2 = \dfrac{1}{1 - \frac{k_1^2}{9}(\ell^3 - x^3)^2}$ ---(38)

By definition:

$$L = \int_0^{\ell} \sqrt{1+p^2}\,dx \quad \text{------------------}(39)$$

Substitute (38) into (39):

$$L = \int_0^{\ell} \frac{dx}{\sqrt{1 - \frac{k_1^2}{9}(\ell^3 - x^3)^2}} \quad \text{----------}(40)$$

To solve Equation (40) the quantity under the radical may be approximated by a series; thus:

$$\left[1 - \frac{k_1^2}{9}(\ell^3 - x^3)^2\right]^{-1/2} = 1 + \frac{k_1^2}{18}(\ell^3 - x^3)^2 + \frac{k_1^4}{216}(\ell^3 - x^3)^4$$

$$+ \frac{5k_1^6}{11664}(\ell^3 - x^3)^6 + \quad \text{-----------------}(41)$$

The bending length $c = \left(\frac{EI}{w}\right)^{1/3}$ as defined in (22), may be substituted into (34):

$$k_2 = \frac{1}{2c^3} \quad \text{----------------------}(42)$$

Rewriting (27):

$$F = \frac{(b+\ell)^2 - b^2}{(b+L)^2 - b^2} = \frac{2b\ell - \ell^2}{2bL - L^2} \quad \text{---------}(43)$$

Solving Equation (43) for ℓ:

$$\ell = -b + \sqrt{b^2 + F(2bL + L^2)} \quad \text{----------}(44)$$

Since $L = a - b = a\,(1-\beta)$, Equation (44) reduces to:

$$\ell = a\left[\sqrt{\beta^2 + F(1-\beta^2)} - \beta\right] \quad \text{-----------}(45)$$

For any experimental value of F at any ratio of β the value of ℓ may be calculated. Equation (40) may now be solved by combining equations (41), (42), and (45), as follows:

(i.) With 2 terms of Equation (41):

$$L = \int_0^{\ell}\left[1 + \frac{k_1^2}{18}(\ell^3 - x^3)^2\right]dx = \ell\left\{1 + \frac{1}{112}\left[\frac{(\ell)}{(c)}\right]^6\right\} \quad \text{----------------------}(46)$$

Rewriting (46) in terms of the effective bending length:

$$c_e = \ell \left[\frac{\ell}{112\,(L-\ell)} \right]^{1/6} \text{ ------------(47)}$$

(ii) With 3 terms of Equation (41):

$$L = \int_0^{\ell} \left[1 + \frac{k_1^2}{18} (\ell^3 - x^3)^2 + \frac{k_1^4}{216} (\ell^3 - x^3)^4 \right] dx$$

$$L = \ell \left\{ 1 + 0.008929 \left[\frac{(\ell)}{(c)} \right]^6 + 0.000155 \left[\frac{(\ell)}{(c)} \right]^{12} \right\} \text{ ------------------------ (48)}$$

From Eq. 48, the value of c may be determined in the following form:

$$c_e = \ell \left[\frac{1}{\sqrt{f\left(\frac{L}{\ell}\right)}} \right]^{1/6} \text{-- (49)}$$

(iii) With 4 terms of Equation (41):

$$L = \int_0^{\ell} \left[1 + \frac{k_1^2}{18} (\ell^3 - x^3)^2 + \frac{k_1^4}{216} (\ell^3 - x^3)^4 + \frac{5k_1^6}{11664} (\ell^3 - x^3)^6 \right] dx \text{ ------------(50)}$$

$$L = \ell \left\{ 1 + 0.008929 \left[\frac{(\ell)}{(c)} \right]^6 + 0.000155 \left[\frac{(\ell)}{(c)} \right]^{12} + 0.000003 \left[\frac{(\ell)}{(c)} \right]^{18} \right\} \text{-----------(51)}$$

c_e may be determined by successive trials.

In the case of L = 3 inches @ $\beta = 0.4$, the effective bending lengths were calculated for comparison. The results are tabulated in Table 11 and plotted in Figure 14.

Figure 15 compares the effective bending length, c_e, with the experimental strip bending test data, c_s. A 1 to 1 correlation line is also shown as a guide.

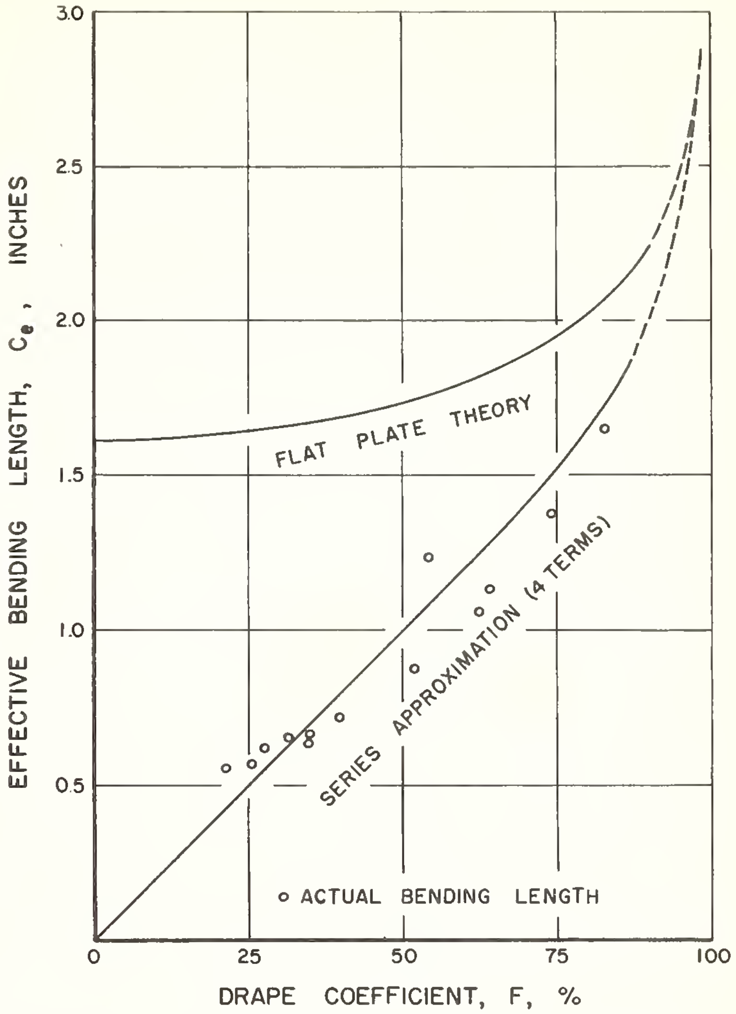

Figure 14.—Effecting bending length, C_e, vs. drape coefficient, F, % for $r_o = 5''$, $r_i = 2''$.

Table 11.—*Effective Bending Lengths for L = 3 inches @ $\beta = 0.4$*

Drape Coefficient, % F	ℓ	Effective Bending Lengths, c_e		
		2 Terms	3 Terms	4 Terms
	Inches	*Inches*	*Inches*	*Inches*
0	0.0	0.0	0.0	0.0
10	.470	.162	.202	--------
20	.864	.339	.396	——
30	1.209	.515	.591	.619
40	1.521	.696	.779	--------
50	1.808	.881	.968	.997
60	2.074	1.080	1.164	--------
70	2.324	1.300	1.376	1.396
80	2.561	1.565	1.627	--------
90	2.785	1.945	1.989	--------
100	3.000	Infinite	Infinite	Infinite

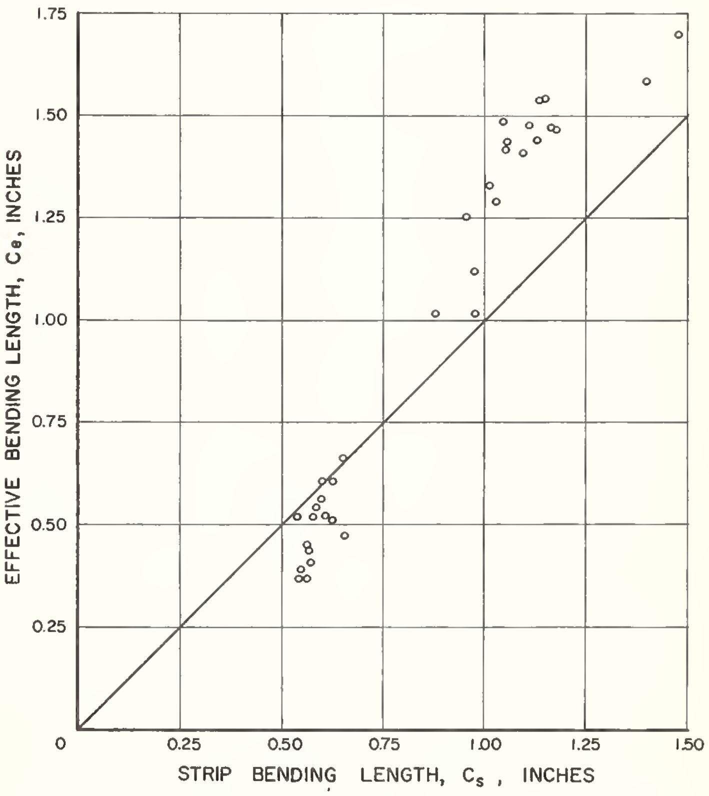

Figure 15.—Strip bending length vs. effective bending length.

Two sources of error in the flat plate theory were the existence of large deflections, and the assumption of a straight line for the deflection curve. As another approach, and one that would partially obviate these errors, analysis was made of a flat strip cantilever beam bending under its own weight, the analysis of which beam would include the effect of large deflections on the curvature of the bent beam. The inclusion of the denominator in the right side of Equation (32) corrects the curvature to that for large deflections. However, the bending moments, M, as written in Equation (32) are valid only for the undistorted position of the strip, and in the case of large deflections would be in error. Hence, the development here is not rigorous.

In spite of this error, the overall agreement obtained in using the formulas is good, as shown in Figure 15. Further work on refining this analysis will be part of the future work on this research. It is planned to study the large deflections of a pie-shaped cantilever beam since this beam shape would be more representative of the structural element of the fabric undergoing deformation than a simple strip.

B. Effect of Support Size

1. Selection of Support Size

The sample size adopted for tests on the Drapemeter is 10 inches in diameter (see part C of this section). The problem of selecting the proper support size is an important one. Table 12 lists the Drape Coefficients of a variety of fabrics tested with different support sizes. It can be seen that with 4-, 5-, and 6-inch supports, (i.e., at $\beta = 0.4$, 0.5, and 0.6 on 10 inch samples) the ranges of Drape Coefficients are widest. Hence it is reasonable to presume that small differences in drapability can most easily be observed here.

Of the three support sizes considered, the 5-inch one was chosen as the standard. The 4- and 6-inch ones were eliminated because of the relative disadvantages, given below:

With the 4 inch support, the amount of overhang is 3 inches. Frequently with more drapable samples, re-entrant folds were formed. The term "re-entrant fold" refers to the parts of a draped sample which pleats in such a way as to be under the projection of the supporting disk. The dotted lines in Figure 16 illustrate the re-entrant folds. Since both the specimen and the support are opaque, the scanning system of the Drapemeter can record only the area outside the outline of the supporting disk, as shown by the solid lines in Figure 16. This results in erroneous data and thereby renders the test useless.

Table 12.—*Effect of Support Size on Drape Coefficient of 10 inch Specimens*

Fabric No.	Drape Coefficient[1], F, at various β's[2]					Bending Length, c
	0.4	0.5	0.6	0.7	0.8	
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Inches*
35	21.9	26.7	34.3	48.2	74.7	0.55
38	27.8	34.7	46.6	63.3	87.5	.62
5	26.0	41.8	54.4	70.1	85.0	.57
23	35.6	42.5	57.9	73.9	87.3	.63
11	32.0	46.6	61.7	75.7	90.7	.65
41	35.5	56.8	61.0	74.5	93.1	.67
26	41.6	51.5	65.8	80.5	95.5	.71
22	53.0	63.8	74.7	88.8	95.7	.87
40	54.5	66.9	77.6	90.7	97.6	1.23
15	65.5	72.1	83.8	86.9	98.5	1.12
30	65.2	76.4	87.5	93.7	98.5	1.05
20	75.3	86.2	88.5	90.2	91.2	1.37
19	84.3	88.9	97.5	98.1	99.0	1.57

[1] Averaged from 6 values.

[2] β = ratio of support disk diameter to sample diameter.

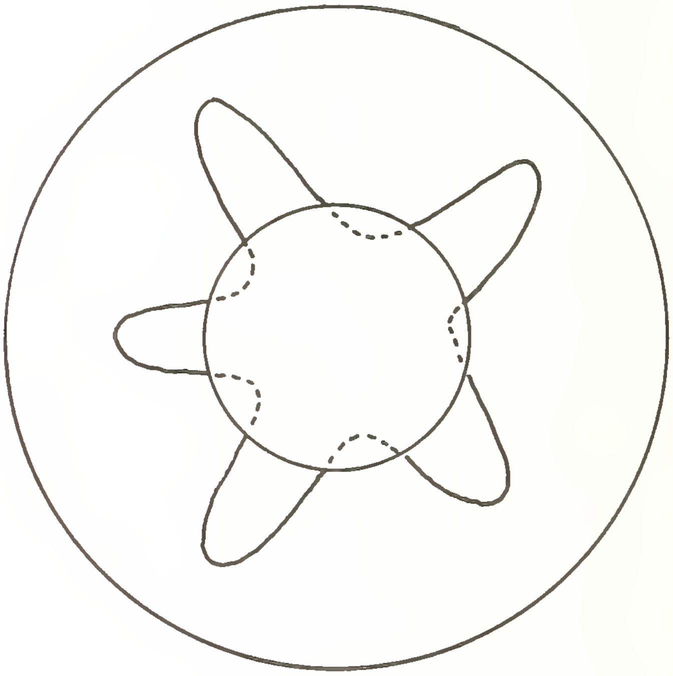

Figure 16.—Re-entrant folds.

The range of Drape Coefficients obtainable with a 6-inch support is equally as good as that obtained with either the 4-inch or 5-inch support. However, referring to the lower curve (series approximation, four terms) of Figure 14, it is seen that the curve is essentially linear up to a Drape Coefficient of 75%, beyond which point the sample incremental increase in stiffness (or effective bending length) produces a much smaller increase in Drape Coefficient. This indicates that the Drapemeter is not operating at its most sensitive portion. Since the Drape Coefficients for the 5-inch support ranged from 26.7% to 88.9% and those for the 6-inch support range from 34.3% to 97.5%, the former is more desirable. Thus the 10-inch samples and the 5-inch support were adopted as standard.

Infrequently, however, it was unsuitable to adhere to the standard test conditions, because of the nature of the sample to be tested. This occurred when the sample was either extremely limp or excessively stiff. A limp fabric formed re-entrant pleats, while the stiff fabric gave Drape Coefficients beyond the linear portion of the curve. Hence it became advisable to perform the test at conditions other than the standard and then to convert the data to the standard condition for comparison and evaluation.

2. Conversion of Data to Standard Conditions.

The experimental points plotted on the lower curve of Figure 14 (data taken from Table 12) generally show good agreement with the theoretically calculated relationship of stiffness (effective bending length) to the Drape Coefficients. It is not unreasonable then, to accept the relationship derived from Part A,2 of this section (i.e., Equations 45, 47, 49, and 51) for trial analyses.

It was assumed that for any given fabric the effective bending length, c_e, would remain constant regardless of test conditions. Thus from the known Drape Coefficient under one set of test conditions, one can calculate what the Drape Coefficient would be under different conditions with a reasonable degree of accuracy.

For simplicity, Equations (45) and (47) were used:

$$\ell = a\left[\sqrt{\beta^2 + F(1-\beta^2)} - \beta\right] \text{-----}(45)$$

$$c_e = \ell\left[\frac{\ell}{112(L-\ell)}\right]^{1/6} \text{-------------------}(47)$$

$\beta = b/a$
$L = a - b$, inches.
ℓ = Projection of L in a draped state, inches.
F = Drape Coefficient/100
c_e = Effective bending length, inches.

Solution of (45) and (47) yielded the values given in Table 13 and plotted in Figure 17.

Table 13.—*Effective Bending Lengths at Constant Drape Coefficients for Various Values of* β [1]

Drape Coefficient, % F	Effective Bending Lengths, c, @ Various Indicated β's [1]				
	0.4	0.5	0.6	0.7	0.8
	Inches	*Inches*	*Inches*	*Inches*	*Inches*
0	0.0	0.0	0.0	0.0	0.0
10	.162	.118	.084	.059	.035
20	.342	.257	.187	.128	.081
30	.517	.396	.296	.208	.132
40	.694	.544	.411	.292	.185
50	.894	.700	.539	.382	.246
60	1.031	.865	.668	.481	.309
70	1.301	1.052	.816	.593	.385
75	1.428	1.152	.902	.658	.428
80	1.564	1.273	.997	.733	.478
85	1.724	1.412	1.109	.816	.533
90	1.950	1.596	1.257	.923	.609
95	2.368	1.888	1.483	1.094	.723
100	Infinite	Infinite	Infinite	Infinite	Infinite

[1] β = Ratio of support disk diameter to sample diameter.

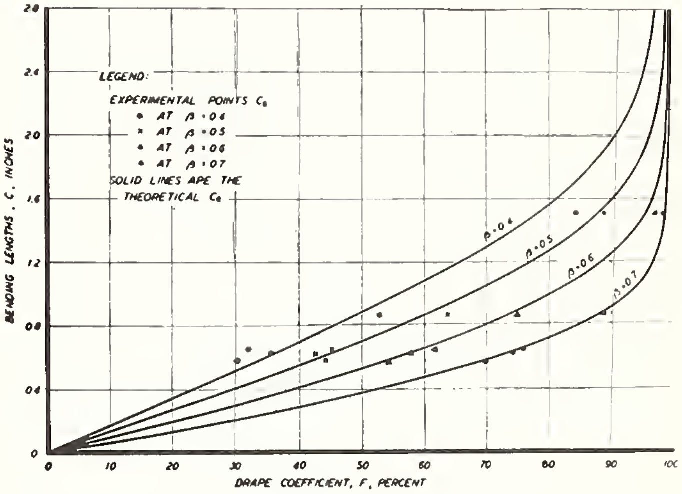

Figure 17.—Effective bending length, C_e, vs. drape coefficient, F, %.

3. Experimental Check

To check the validity and accuracy of the theoretical curves of Figure 17, the experimental data in Table 12 are plotted on Figure 17.

This figure should be interpreted as follows:

a. The curves are all theoretical, calculated from Equations (45) and (47). They show how percent F should vary for a given fabric as the coefficient β is changed. This variation is determined by the intersection of the curves with any value of c_e, which value is an inherent fabric property.

b. The plotted points represent experimental values of F at the various values of β. Any one fabric is represented by the series of points along a horizontal (constant c_e) line.

It is apparent, from Figure 17, that the experimental change in percent F of a given fabric (with c_e) for changes in β checks the theoretical value as given by the curves. The greatest deviations of experimental values from the theoretical curves occur for fabrics whose bending properties in the warp and fill directions differ to a large degree. Since the curves were calculated assuming isotropy, this deviation is to be expected.

C. Effect of Sample Size

1. Selection of Sample Size

The selection of sample size demands consideration equal to that given to the selection of supporting disk size. To insure proper randomizing of specimens from a sample swatch, a fairly large piece of material is required. It is obvious that the larger the size of samples, the larger the swatch must be. Although some tests in this research project have been made with only three samples from each fabric, the preferred number to obtain a reliable mean is at least five. Thus with the standard 10-inch samples, a reasonable size for a swatch would be about 8 or 10 square feet. In the case of the more expensive materials, the use of samples much larger than 10 inches might be uneconomical. On the other hand, samples smaller than 10 inches tend to diminish the sensitivity of the Drapemeter. In addition, with a sample diameter of 10 inches, the diameters of the supporting disks having the common values of β (0.4, 0.5, 0.6, and 0.7) become convenient dimensions for calculation purposes.

Table 14 lists the Drape Coefficients of eight fabrics tested with sample diameters of 8, 10, and 12 inches. In each case the support diameter was one-half of the sample diameter ($\beta = 0.5$). It is seen that with the 8 inch samples, the useful range of Drape Coefficients, i.e., linear portion of the curve, is rather limited. On the other hand, with either 10 or 12 inch samples, the ranges are much wider. However, the use of 12 inch samples involves three distinct disadvantages; namely:

a. Fabrics more drapable than No. 35 might have a tendency to form re-entrant folds as discussed in Part B-1 above if the same value of β were used.

b. With the exception of $\beta = 0.5$ where the support size is 6 inches all the other values of β would require supports diameters of fractional inches.

c. For the same number of tests as are run with 10 inch samples, at least 44% more material would be necessary.

Table 14.—*Effect of Sample Size, $\beta = 0.5$[1] on F.*

Fabric No.	F[2] with various sample diameters			Bending Length
	8″	10″	12″	
	Percent	*Percent*	*Percent*	*Inches*
35	36.3	26.7	21.5	0.55
38	47.0	34.7	28.0	.62
11	60.1	46.6	35.5	.65
41	64.1	46.8	36.4	.67
26	69.1	51.5	43.1	.71
40	71.9	66.9	53.8	1.23
30	84.5	76.4	63.9	1.05
20	[3]	86.2	85.2	1.37

[1] $\beta = 0.5$, that is, support disk diameter = ½ sample diameter.

[2] Averaged from 6 tests.

[3] The Drape Coefficient at this point approaches 100%; the data is inaccurate.

2. Conversion of Data to Standard Conditions.

The equations from which the relationships between data taken from tests employing different support sizes were calculated may be used here. Rewriting Equation (47):

$$L = \ell \left\{ 1 + \frac{1}{112} \left[\left(\frac{\ell}{c} \right) \right]^6 \right\} \quad \text{---------} (52)$$

Where (referring to Figure 18):

r_o = Radius of sample, inches

r_1 = Radius of support, inches

$\bar{r}$ = Mean Radius of draped sample, inches

$a = \bar{r}/r_o$ and $\beta = r_i/r_o$

$L = r_o - r_i$ and $\ell = \bar{r} - r_i$

c_e = Effective bending length, inches.

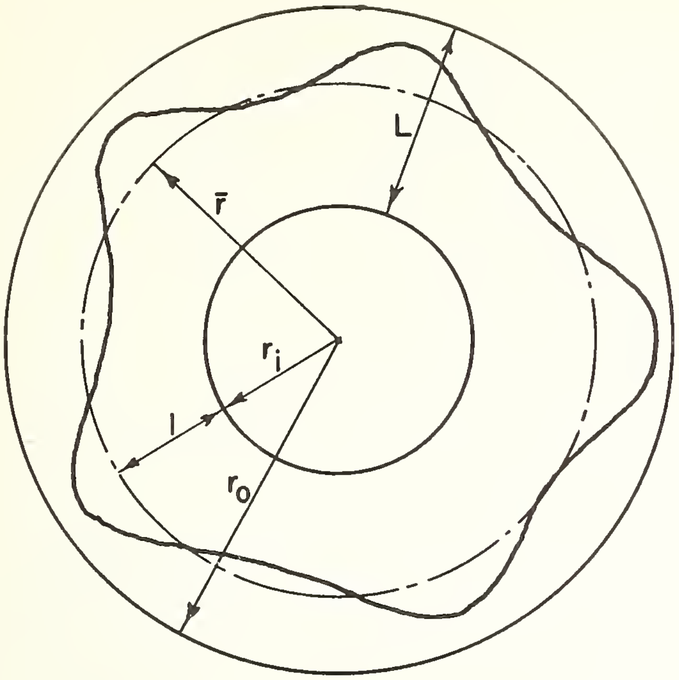

Figure 18.—Components of a drape.

Rewriting Equation (52):

$$r_o - r_i = (\bar{r} - r_i)\left\{1 + \frac{1}{112}\left[\frac{(\bar{r} - r_i)}{(c)}\right]^6\right\}$$

or:

$$\frac{r_o - r_i}{\bar{r} - r_i} = 1 + \frac{1}{112}\left[\frac{(\bar{r} - r_i)}{(c)}\right]^6$$

dividing by r_o and substituting $\alpha = \bar{r}/r_o$ and $\beta = r_i/r_o$:

$$\frac{1 - \beta}{\alpha - \beta} = 1 + \frac{1}{112} \times \frac{r_o^6 (\alpha - \beta)^6}{o^6}$$

Simplifying:

$$c^6 = \frac{r_o^6 (\alpha - \beta)^7}{112 (1 - \alpha)} \quad \text{-------------(53)}$$

And from Equation (45):

$$F = \frac{\alpha^2 - \beta^2}{1 - \beta^2} \quad \text{---------------(54)}$$

Thus it is possible to convert the Drape Coefficient found for any sample size (at constant β) to that for a different sample size:

$$\frac{r_{o1}^6 (\alpha_1 - \beta)^7}{1 - \alpha_1} = \frac{r_{o2}^6 (\alpha_2 - \beta)^7}{1 - \alpha_2}$$

3. Experimental Check

The measured F values given in Table 14 were substituted into Eq. 54, and values of α considered to be measured values, determined therefrom. Using Eq.55, theoretical values of α_2 for varying sample sizes r_{o2} were calculated, employing the measured values of α, for 10 inch sample sizes as a base. The measured and calculated values of α so found may then be compared. The results are tabulated in Table 15 and are plotted in Figure 19. The agreement between the calculated and measured values of α appears to be good.

D. Drape Geometry

Drape geometry, i. e., the study of the configuration of the draped sample, is actually the most important phase in the understanding of the mechanism of drape. The drape diagram, as taken from the Drapemeter charts, is merely a simplification of a three dimensional drape sample to its two dimensional projection. In the research project the vertical component was neglected for ease of handling. From the drape diagram, three items are of significance, namely the area, the number of nodes, and the shape of the nodes. These are discussed at length below.

Table 15.—*Effect of Sample Size on Values of* α

$$\left(\alpha = \frac{\bar{r}}{r_o},\ \beta = \frac{r_i}{r_o},\ \text{and } F = \frac{\alpha^2 - \beta^2}{1 - \beta^2}\right) @\ \beta = 0.5$$

Fabric No.	Measured 10″ Samples	8″ Samples		12″ Samples	
		Measured	Calculated [1]	Measured	Calculated [1]
35	0.671	0.723	0.704	0.641	0.648
38	.714	.776	.754	.678	.686
11	.774	.837	.821	.709	.739
41	.775	.855	.822	.723	.740
26	.798	.876	.847	.757	.762
40	.867	.890	.916	.802	.826
30	.909	.941	.950	.854	.867
20	.947	------	------	.943	.911

[1] Calculated from the 10-inch measurements.

1. Area

The area enclosed by the drape diagram and the calculations therefrom were the basis of the Drape Coefficient, percent F, which has been previously described. To review briefly, percent F, may be expressed as follows:

$$\%F = \frac{A - A_d}{A_D - A_d} \times 100 \quad \text{----------------(56)}$$

where:

A = Area recorded on the integrator,
A_d = Area of the supporting disk,
A_D = Area of the sample.

To aid calculations, Equation (56) may be rewritten:

$$\%F = C_1 A - C_2 \quad \text{-----------------(57)}$$

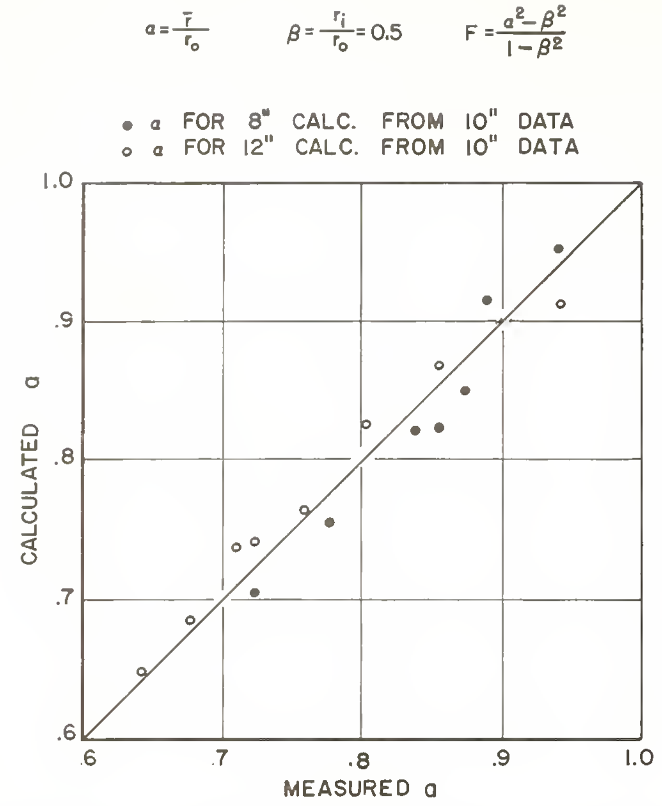

Figure 19.—Measured and calculated values of α.

For the standard 10-inch samples, the constants C_1 and C_2 for any support size are given below:

$\beta = 0.3(r_i = 1.5", r_o = 5")$ $\%F = 1.399A - 9.89$ ---------------- (58)

$\beta = 0.4(r_i = 2.0", r_o = 5")$ $\%F = 1.516A - 19.05$ ---------------- (59)

$\beta = 0.5(r_i = 2.5", r_o = 5")$ $\%F = 1.698A - 33.33$ ---------------- (60)

$\beta = 0.6(r_i = 3.0", r_o = 5")$ $\%F = 1.989A - 56.25$ ---------------- (61)

$\beta = 0.7(r_i = 3.5", r_o = 5")$ $\%F = 2.497A - 96.08$ ---------------- (62)

$\beta = 0.8(r_i = 4.0", r_o = 5")$ $\%F = 3.537A - 177.77$ ---------------- (63)

2. Number of Nodes

Nodes, or pleats, are formed in a draped sample by virtue of the buckling of the material. Figure 18 shows a typical drape diagram; the circumference of the circular sample is $2\pi r_o$. In the draped position this length oscillates about the circumference of the mean circle, which circumference is $2\pi\bar{r}$. Since $2\pi\bar{r}$ is less than $2\pi r_o$ ($\bar{r}$ being less than r_o), buckling must occur, hence pleat formations.

The phenomenon of buckling is related to the elastic properties of the material and the type of load application. At the present stage of this research, very little is known about the buckling behavior of textile materials. Hence, only general observations are reported here. The general problem has several aspects worthy of consideration and these are listed below with illustrative data.

a. *Theories of buckling.* The draped sample may be considered as a circular plate whose periphery buckles under its own weight. Classical approaches in the solution of plate buckling are described to a limited extent in the literature; however, these approaches will not apply directly to fabric structures. Future study of this subject appears to be in order.

b. *Number of nodes.* The nodes are formed in a draped sample almost entirely at random. The inherent physical properties of the material cause a range to exist for the number of nodes which are formed. Since it is impossible to have a fractional number of nodes, it is obvious that, for a given set of test conditions, the sample may form N number of nodes at one time and N $\pm$ 1 number of nodes at another. A study was made to analyze such a distribution of the number of nodes.

One hundred and six drape diagrams were taken from this number of 10 inch diameter samples of No. 27 fabric tested on the Drapemeter, with $\beta = 0.5$. Table 16 lists the distribution of nodes falling between 4 and 9, inclusive, as counted from the drape diagrams. Attention should be called to the fact that, although the same material was used throughout these 106 tests, the Drape Coefficients increased with the increase in the number of nodes. The differences between the Drape Coefficients of the 5-node and the 6-node diagrams and between the 6-node and the 7-node diagrams

Table 16.—*Distribution of Node Formations* [*106 tests of fabric No. 27, 10 inch samples @ $\beta = 0.5$*]

Range of Nodes	Tests Showing Occurrences		F
	Number	*Percent*	*Percent*
4	0	0.0	-------
5	29	27.4	48.3
6	61	57.5	51.1
7	14	13.2	53.1
8	2	1.9	53.9
9	0	.0	-------

were statistically significant in both cases. This is understandable, considering the following: For a material with a given critical buckling length to fall into two different configurations, say one having 6 nodes and the other having 7, the one with the 7 nodes would have to protrude out further if its buckling length were to be maintained the same as that of the 6 node sample.

However, in the normal test procedure, only 10 tests (both sides of 5 specimens) were made on each fabric. This precludes any possibility or feasibility of making an analysis of node distribution.

In addition to a distribution of number of nodes within any particular material, the number of nodes also varies with the test conditions (i.e., β and sample size). Figure 20 plots the number of nodes, N, against β, for samples 8, 10, and 12 inches in diameter. The individual points of this graph do not show any correlation between Drape Coefficients and number of nodes. However, it is seen that for any value of β there can be only a narrow range to the number of nodes.

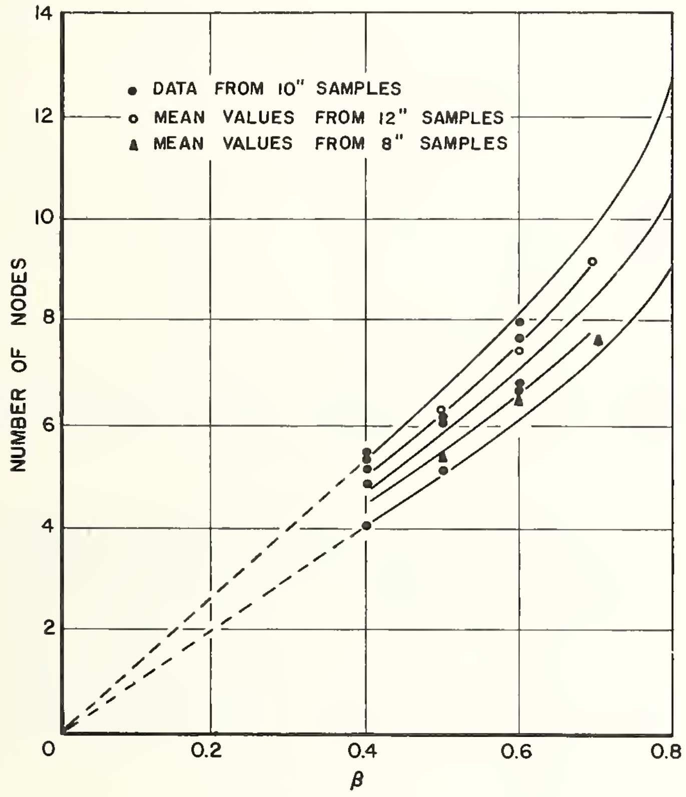

Figure 20.—Number of nodes vs. β.

C. *Chord Length.* A node is defined as that portion of the fabric between two consecutive points whose radial distance from the center is least. Assuming that all nodes in a drape diagram are uniform in shape, then the central angle, θ, subtended by a pleat equals 360° divided by the number of nodes. N. The chord length, C, on the supporting disk equals $2r_i$ sine $\frac{\theta}{2}$, or $C = 2r_1$ sin (180/N), (See Fig. 21.) Typical values of C for a variety of fabrics under different test conditions are given in Table 17. The significance of these values has not yet been fully evaluated.

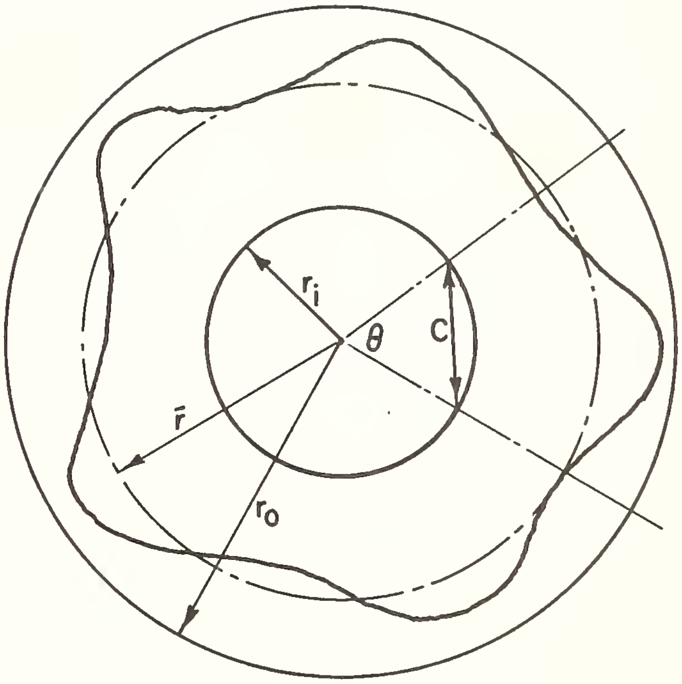

Figure 21.—Chord length of a node.

3. Shape of the Nodes

The discussions that follow are based on the assumption that the nodes in a drape diagram are uniform. Hence the drape diagram becomes a cyclic function in polar coordinates. The task of analysis can be made very much simpler by means of transferring the polar coordinates into rectangular coordinates (Fig. 22,A). The shape of this cyclic function can be approximated by familiar geometric forms.

a. *Assumed Shapes.* Consider a single node, the shape of which may take the form of the triangle, the sin function, the parabola, the circular arc, the semicircle, the complete cycloid, the semiellipse, or the rectangle, etc., as shown in the composite plot of Figure 23. All of these shapes listed are definable by

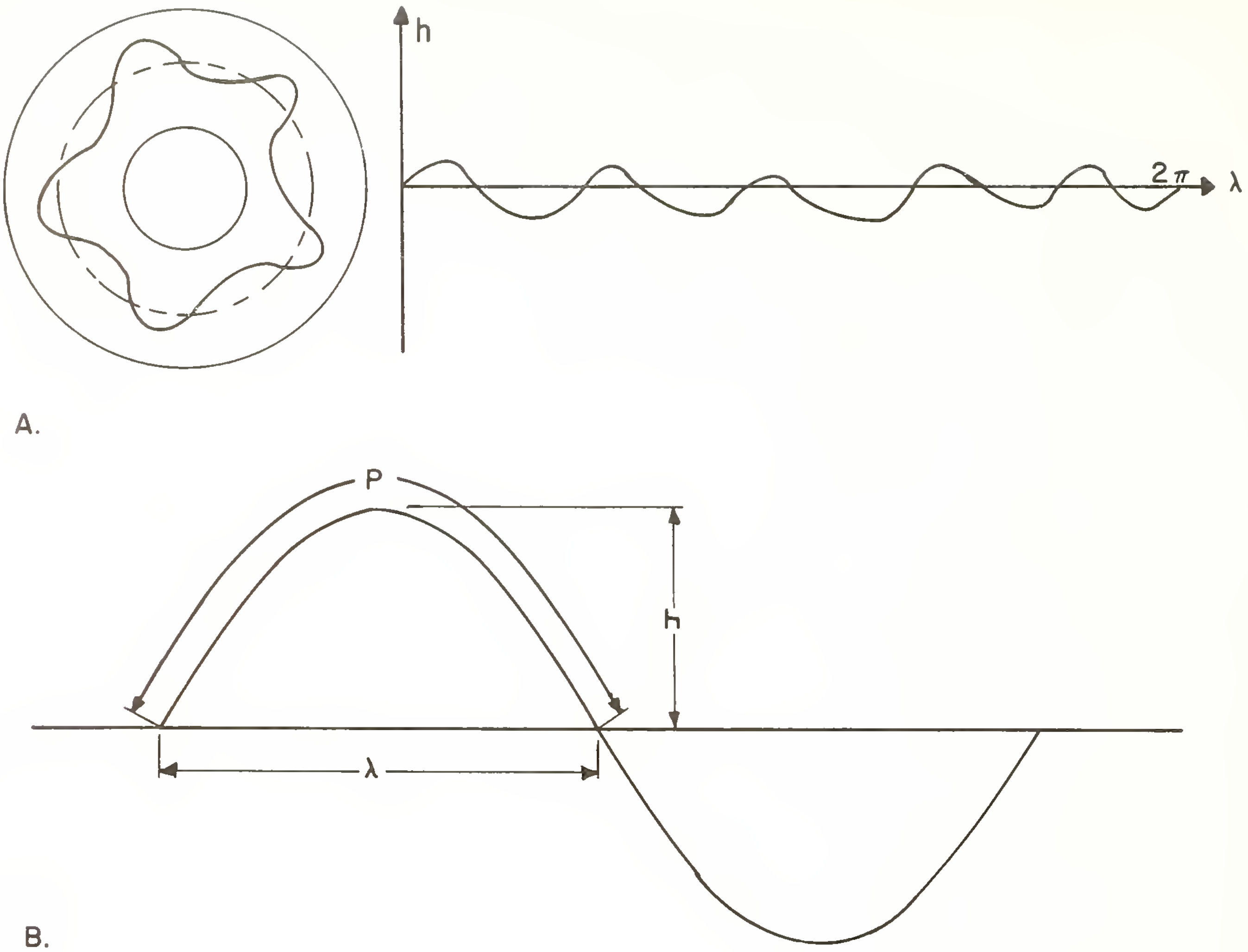

Figure 22.—**A.** Drape diagram: Conversion of palar cordinate to rectangular coordinates; **B,** the components of a node.

three variables, as shown in Figure 22,B: the wavelength, λ; the amplitude, h; and the perimeter, p. The sum of the perimeters of all the nodes in a drape diagram is equal to the circumference of the sample, $2\pi r_o$, except for second order effects. The ratio of wavelength over amplitude, λ/h, depends on the Drape Coefficient; i.e., if the number of nodes, N, were fixed then λ/h varies inversely with the Drape Coefficient. This relationship for the above mentioned configurations can be derived as follows:

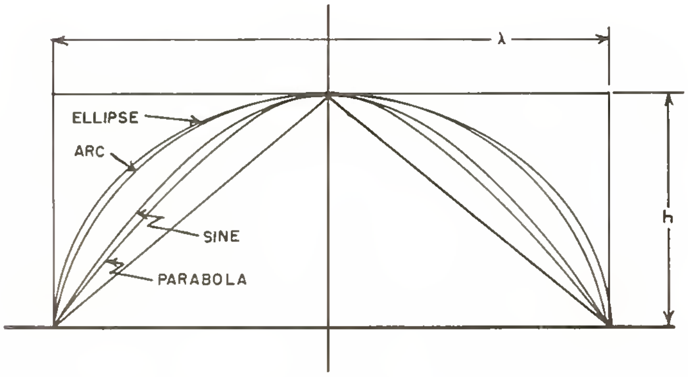

Figure 23.—Possible shapes of nodes.

i. The triangle (Fig. 24).

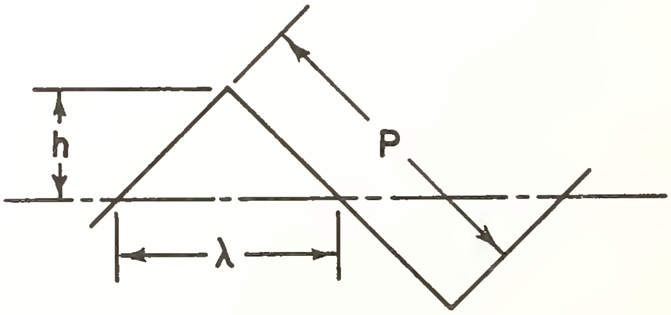

Figure 24.—The triangle.

Table 17.—*Drape Coefficients and Node Distribution*

Fabric No.	β	F	N	C	F	N	C	F	N	C
		8″ Sample			10″ Sample			12″ Sample		
		Percent		*Inches*	*Percent*		*Inches*	*Percent*		*Inches*
35	0.4	28.2	4.9	1.91	21.9	5.3	2.24	16.0	----	--------
	.5	36.3	5.6	2.13	26.7	5.7	2.62	21.5	----	--------
	.6	49.5	6.7	2.17	34.3	6.7	2.71	27.9	8.7	2.54
	.7	67.7	7.7	2.22	48.2	8.3	2.59	36.5	8.7	2.97
38	.4	38.2	4.9	1.91	27.8	5.2	2.27	20.1	----	--------
	.5	47.0	5.3	2.24	34.7	5.5	2.70	28.0	----	--------
	.6	62.7	7.3	2.01	46.6	6.2	2.91	36.4	7.8	2.82
	.7	78.4	7.4	2.30	63.3	7.7	2.78	50.1	8.8	2.94
11	.4	49.7	4.7	1.98	32.0	5.2	2.27	25.9	----	--------
	.5	60.1	5.5	2.16	46.6	6.0	2.50	35.5	7.2	2.54
	.6	72.0	7.1	2.06	61.7	7.7	2.38	45.0	7.8	2.82
	.7	83.1	7.2	2.37	75.7	8.2	2.62	60.3	9.3	2.79
41	.4	52.0	5.2	1.82	35.5	5.0	2.35	26.0	----	--------
	.5	64.1	5.8	2.06	46.8	6.5	2.32	36.4	6.4	2.83
	.6	76.1	7.9	1.86	61.0	7.7	2.38	47.0	7.8	2.82
	.7	85.5	8.4	2.04	74.5	8.8	2.45	67.0	10.0	2.60
26	.4	59.5	5.0	1.88	41.6	4.8	2.44	30.6	----	--------
	.5	69.1	5.9	2.03	51.5	6.0	2.50	43.1	6.0	3.00
	.6	79.7	7.0	2.08	65.8	6.8	2.68	53.8	7.5	2.93
	.7	87.6	7.1	2.40	80.5	8.3	2.59	70.4	9.8	2.65
40	.4	61.2	4.4	2.10	54.5	4.2	2.72	40.9	5.0	2.82
	.5	71.9	4.2	2.72	66.9	4.7	3.10	53.8	6.3	2.87
	.6	86.3	4.0	3.39	77.6	4.6	3.78	64.3	6.3	3.48
	.7	94.3	----	--------	90.7	----	--------	--------	----	--------
30	.4	77.5	3.7	2.40	65.2	4.0	2.83	51.1	4.4	3.14
	.5	84.5	3.6	3.06	76.4	5.2	2.84	63.9	5.4	3.29
	.6	91.3	----	--------	87.5	6.8	2.68	74.4	6.2	3.49
	.7	--------	----	--------	93.7	----	--------	--------	----	--------
20	.4	93.6	----	--------	75.2	5.2	2.27	57.7	4.0	3.39
	.5	--------	----	--------	86.2	5.7	2.62	85.2	----	--------
	.6	--------	----	--------	88.5	8.0	2.30	--------	----	--------
	.7	--------	----	--------	90.2	----	--------	--------	----	--------

It is clear that:

$$p = 2\sqrt{h^2 + (\lambda/2)^2} \quad \text{-----------------} (64)$$

Since the sum of all the perimeters, p, of the drape diagram is the same as the circumference of the undraped sample, $2\pi r_o$, then:

$$2pN = 2\pi r_o \quad \text{..........................} (65)$$

By definition, the sum of the wavelengths, $2\lambda N$, must be equal to the circumference of the mean circle; $2\pi r$:

$$2\lambda N = 2\pi \bar{r} \quad \text{..........................} (66)$$

Combining Equations (64), (65), and (66):

$$\frac{r_o}{\bar{r}} = \frac{2\sqrt{h^2 + (\lambda/2)^2}}{\lambda} \quad \text{---------------} (67)$$

Simplifying Equation (67):

$$\frac{h}{\lambda} = \frac{1}{2}\sqrt{\left(\frac{r_o}{\bar{r}}\right)^2 - 1} \quad \text{---------------} (68)$$

The ratio of $r_o/\bar{r}$ can be easily converted to Drape Coefficient at any given value of β by the equation:

$$F = \frac{a^2 - \beta^2}{1 - \beta^2} \quad \text{where} \quad a = \frac{\bar{r}}{r_o} \qquad \text{-(54)}$$

ii. The rectangle (Fig. 25)

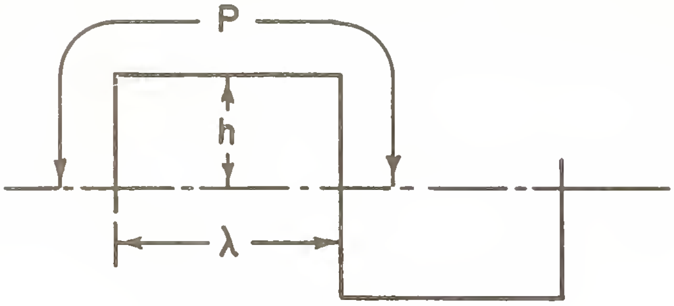

Figure 25.—The rectangle.

The perimeter:

$$p = 2h + \lambda \qquad \text{----------------------(69)}$$

Combining Equations (65), (66), and (69):

$$\frac{h}{\lambda} = \frac{1}{2}\left(\frac{r_o}{\bar{r}} - 1\right) \qquad \text{------------------ (70)}$$

iii. The sine function (Fig. 26).

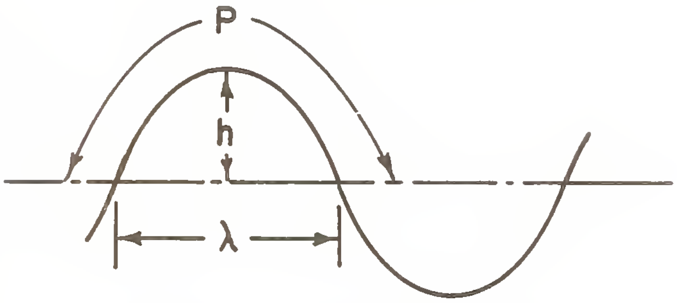

Figure 26.—The sine function

The equation of the sine curve is given by:

$$y = h \sin kx \qquad \text{(71)}$$

where:

$$k = \pi/\lambda \qquad \text{(72)}$$

The length of any curve may be written as:

$$p = \int \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\, dx \qquad \text{-------------- (73)}$$

Differentiating Equation (71):

$$\frac{dy}{dx} = hk \cos kx \qquad \text{-------------------- (74)}$$

Substituting Equation (74) into Equation (73):

$$p = \int^{\lambda} \sqrt{1 + (hk \cos kx)^2}\, dx \qquad \text{----------(75)}$$

From Equation (65) and (66):

$$P = \lambda \frac{r_o}{\bar{r}} \qquad \text{------------------------ (76)}$$

Rewriting Equation (75):

$$p = \sqrt{1+h^2k^2} \int_o^{\lambda} \sqrt{1 - \frac{(h^2k^2)}{(1+h^2k^2)} \sin^2 kx}\, dx \qquad \text{- (77)}$$

Let $U = kx$, then $x = U/k$, and $dx = dU/k$.

Equation (77) becomes:

$$p = \frac{\sqrt{1+h^2k^2}}{k} \int_o^{k\lambda} \sqrt{1 - \frac{(h^2k^2)}{(1+h^2k^2)} \sin^2 U}\, dUJ \qquad \text{- (78)}$$

Let:

$$V = \frac{hk}{\sqrt{1 + h^2k^2}} \qquad \text{--------------------(79)}$$

Combining (72) and (79):

$$v = \frac{\pi \frac{(h)}{(\lambda)}}{\sqrt{1+\pi^2 \left[\frac{(h)}{(\lambda)}\right]^2}} \qquad \text{------------(80)}$$

From (78) and (80):

$$p = \frac{\sqrt{1 + \pi^2 \left[\frac{(h)}{(\lambda)}\right]^2}}{\frac{\pi}{\lambda}} \int_o^{\pi} \sqrt{1 - V^2 \sin^2 U}\, dU \qquad \text{--------(81)}$$

From (76) and (81):

$$\frac{r_o}{\bar{r}} = \frac{1}{\pi}\left[1 + \pi^2 \left(\frac{h}{\lambda}\right)^2\right]^{1/2} E \qquad \text{--------(82)}$$

Where E, the complete elliptic integral, may be readily found in tables:

$$E = \int_o^{\pi} \sqrt{1 - V^2 \sin^2 U}\, dU \qquad \text{-----------(83)}$$

iv. The parabola (Fig. 27).

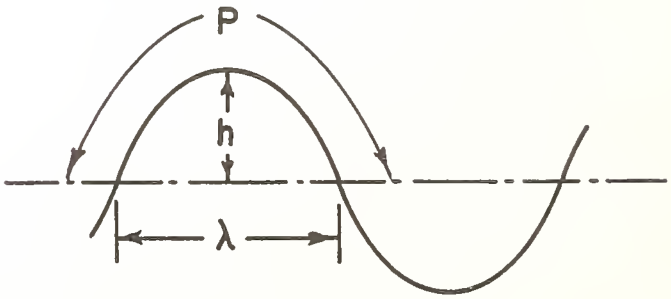

Figure 27.—The parabola

The perimeter of a parabola is given as:

$$p = \frac{1}{2}\sqrt{1 + 16h^2} + \frac{\lambda^2}{8h} \ln \frac{4h + \sqrt{\lambda^2 + 16h^2}}{\lambda} \text{ ------------ } (84)$$

Substituting Equation (76) into (84):

$$\frac{r_o}{\bar{r}} = \frac{1}{2}\sqrt{1 + 16\left(\frac{h}{\lambda}\right)^2} + \frac{1}{8\left(\frac{h}{\lambda}\right)} \ln \left[4\left(\frac{h}{\lambda}\right) + \sqrt{1 + 16\left(\frac{h}{\lambda}\right)^2}\,\right] \text{ -- } (85)$$

v. The circular arc (Fig. 28).

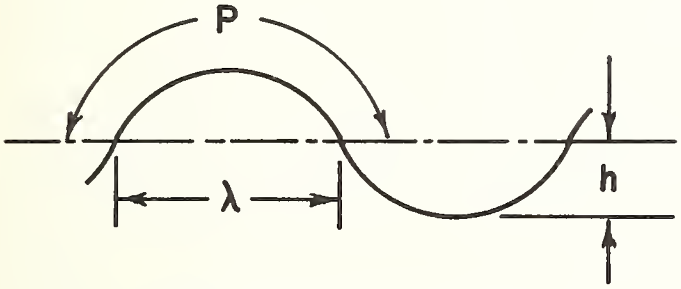

Figure 28.—The circular arc.

From the geometrical configuration:

$$\lambda = 2\sqrt{h\ (2R - h)}$$

or:

$$R = \frac{\lambda^2 + 4h^2}{8h} \text{ ---------------- } (86)$$

$$\theta = 2 \sin^{-1} \frac{\lambda}{2R} \text{ ---------------- } (87)$$

and:

$$p = \theta R \text{ ---------------------- } (88)$$

Substituting (86), (87), and (88) into (76):

$$\frac{r_o}{\bar{r}} = \left\{\left(\frac{\lambda}{4h} \pm \frac{h}{\lambda}\right)\right\} \sin^{-1} \frac{1}{\frac{\lambda}{4h} + \frac{h}{\lambda}} \text{ --- } (89)$$

vi. The semi-ellipse (Fig. 29).

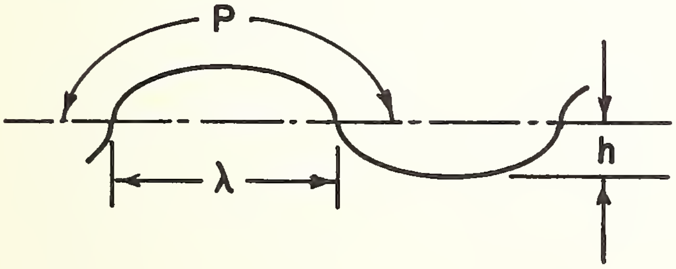

Figure 29.—The semi-ellipse.

Let:

$$R = \frac{\frac{\lambda}{2} - h}{\frac{\lambda}{2} + h} = \frac{1 - 2\frac{h}{\lambda}}{1 + 2\frac{h}{\lambda}} \text{ -----} (90)$$

Then:

$$p = \frac{\pi}{2}\left[\frac{\lambda}{2} + h\right]\left[\left(1 + \frac{R^2}{4} + \frac{R^4}{64} + \frac{R^6}{256} + \cdots\right)\right] \text{ --} (91)$$

Simplifying (90) and substituting into (76):

$$\frac{r_o}{\bar{r}} = \frac{\pi}{4}\left[\left(1 + 2\frac{h}{\lambda}\right)\right]\left[1 + \frac{R^2}{4} + \frac{R^4}{64} + \frac{R^6}{256}\right] \text{ ---} (92)$$

vii. The semicircle and the complete cycloid.

These are not suitable shapes because there can be only one value of h/λ.

viii. Other shapes, such as the hyperbola and partial ellipses.

The shapes considered above cover a fair representation of possible configuration, hence no further studies were made.

Summarizing, the relationship between the Shape Factor, h/λ and the Drape Coefficient (which is expressed in terms of r_o/r for all values of β) for any of these configurations can be calculated by Equations, (68), (70), (82), (85), (89), and (92).

b. *Experimental Check.* Equation (54) may be rewritten as:

$$a = \frac{\bar{r}}{r_o} = \sqrt{\beta^2 + F(1 - \beta^2)} \text{ -------} (93)$$

Table 18.—*Values of* $\frac{\bar{r}}{r}$ *at any Drape Coefficient, F, for Various Values of* β

%F	β = 0.4	β = 0.5	β = 0.6	β = 0.7	β = 0.8
0	0.400	0.500	0.600	0.700	0.800
10	.495	.570	.651	.736	.822
20	.573	.633	.699	.769	.844
30	.642	.689	.743	.802	.865
40	.704	.742	.785	.833	.886
50	.762	.791	.825	.863	.906
60	.815	.837	.863	.892	.925
70	.865	.881	.899	.920	.944
80	.912	.922	.934	.948	.964
90	.957	.962	.968	.974	.982
100	1.000	1.000	1.000	1.000	1.000

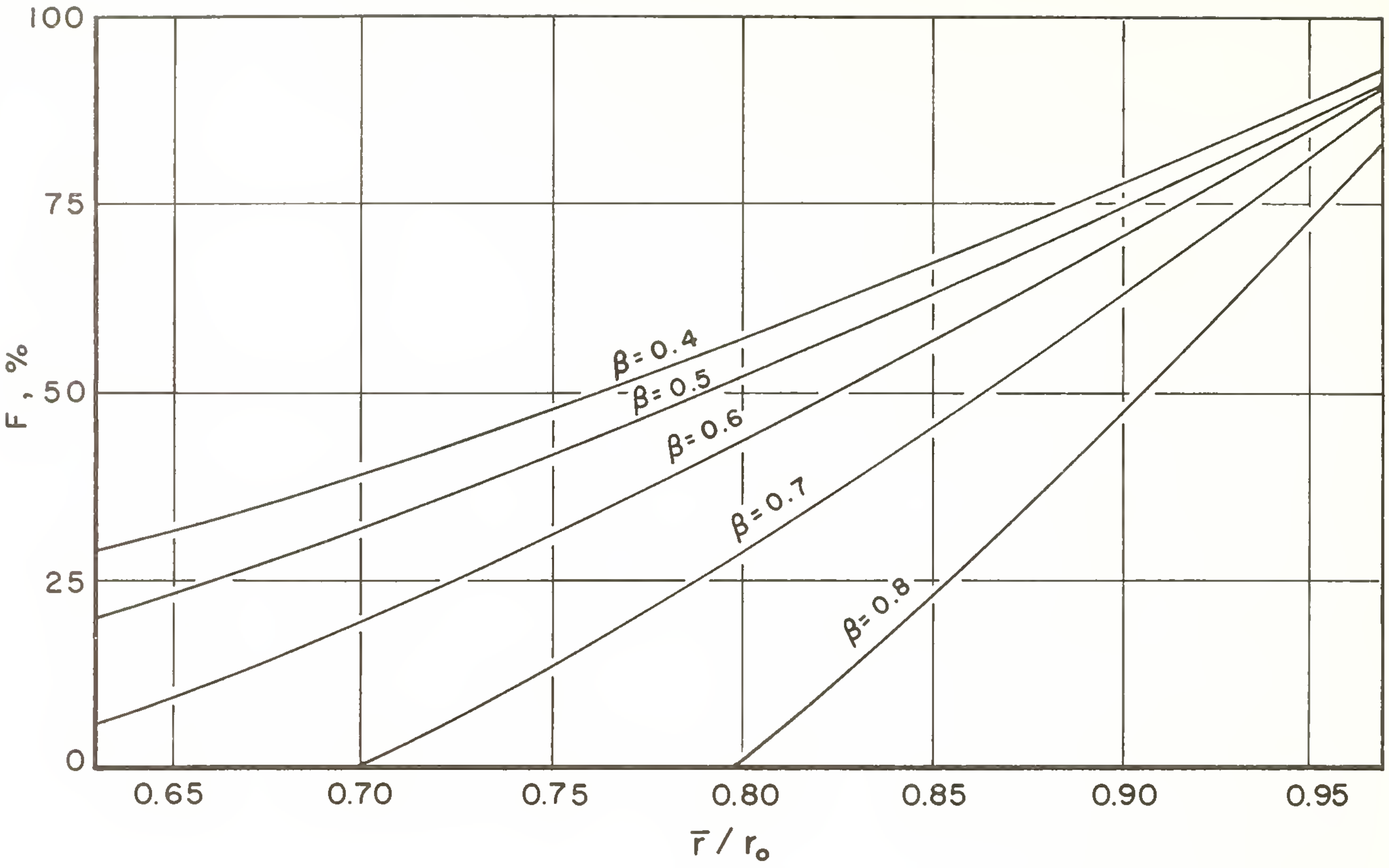

Figure 30.—Drape coefficient vs. $\bar{r}/r_0$.

The values of α are tabulated in Table 18 and plotted in Figure 30. Table 19 and Figure 31 present the values of h/λ at any value of α for the various configurations.

Table 19.—*Values of* $\frac{\bar{r}}{r_0}$ *at any shape factor for Various Configurations*

h/λ	Triangle	Sine	Parabola	Arc	Semi-Ellipse	Rectangle
0.00	1.000	1.000	1.000	1.000	1.000	1.000
.05	.995	.994	.994	.994	.985	.909
.10	.981	.977	.975	.974	.952	.833
.15	.958	.952	.946	.944	.912	.769
.20	.929	.916	.911	.908	.869	.714
.25	.895	.877	.871	.863	.826	.667
.30	.858	.838	.835	.817	.784	.625
.35	.820	.797	.789	.769	.743	.588
.40	.781	.757	.750	.723	.705	.555
.45	.741	.719	.712	.678	.670	.526
.50	.707	.683	.676	.637	.637	.500

Table 20 (Plotted in Fig. 32) lists a few measurements of the Shape Factor, λ/h, as found by experiment. Also given are the calculated values for the semi-ellipse configuration. As is seen from Figure 33, the agreement between calculated and measured Shape Factors is excellent, indicating that this aspect of drape geometry is readily predictable from percent F.

E. The Strip Bending Test for Stiffness

Inasmuch as drape must be related in part to the bending properties of fabrics, an understanding of the strip bending test would be helpful. This test determines the bending length, defined by F. T. Peirce[8] as the length of fabric that will bend under its own weight to a definite extent.

1. Test Procedure

Samples are cut from the fabric to be tested with a dink or a razor blade to a size of 6 inches by 1 inch. The edges of the sample are made to follow the lengthwise threads, warp or filling, as closely as possible. It is desirable that samples should have been handled as little as possible, for bending and folding alter the stiffness and produce lines or crease or weakness that make the result meaningless. The specimen is mounted in the tester as illustrated in

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[8] Peirce, F. T., "The Handle of Cloth as a Measurable Quantity," Journal of the Textile Institute 21: T377-T416, September 1930.

Table 20.—*Measured and Calculated Shape Factors*

Fabric No.	Drape Coefficient, %F@ $\beta = 0.5$	$\bar{r}/r_o$	Shape Factor, h/λ Measured	Shape Factor, h/λ Calculated (Semi-Ellipse)	Fabric No.	Drape Coefficient, %F@ $\beta = 0.5$	$\bar{r}/r_o$	Shape Factor, h/λ Measured	Shape Factor, h/λ Calculated (Semi-Ellipse)
47	24.9	0.661	0.450	0.463	41	56.8	.822	.305	.253
35	26.7	.671	.395	.450	73	57.2	.824	.217	.251
46	31.6	.698	.418	.412	34	57.9	.827	.193	.247
38	34.7	.714	.394	.388	300C	57.9	.827	.228	.247
5	41.8	.751	.277	.340	76	58.1	.828	.208	.246
28	46.6	.774	.308	.312	74	58.6	.830	.212	.245
23	46.8	.775	.287	.310	501A	58.6	.830	.222	.245
402C	47.8	.780	.255	.304	81	58.7	.831	.216	.243
302C	48.7	.784	.278	.300	202A	59.7	.835	.231	.238
502C	49.3	.787	.208	.296	75	60.6	.839	.191	.234
501C	51.0	.795	.275	.286	77	60.8	.840	.196	.233
500C	51.2	.796	.271	.285	400A	61.5	.843	.200	.229
26	51.5	.798	.273	.282	31	62.4	.847	.196	.225
80	51.6	.798	.254	.282	200C	62.4	.847	.213	.225
402A	51.9	.799	.262	.281	22	63.8	.854	.169	.217
502A	52.1	.800	.247	.280	201C	65.0	.858	.191	.212
301C	52.5	.802	.283	.277	300A	65.2	.859	.177	.211
400C	53.1	.805	.253	.273	200A	67.7	.870	.178	.198
79	54.2	.810	.244	.268	201A	68.0	.871	.180	.197
83	54.7	.812	.237	.266	84	71.9	.888	.137	.178
302A	54.7	.812	.251	.266	78	72.0	.889	.134	.177
401A	54.7	.812	.258	.266	15	72.1	.889	.120	.177
500A	54.7	.812	.243	.266	12	73.1	.894	.128	.172
82	55.3	.815	.234	.262	30	76.4	.907	.116	.157
301A	55.3	.815	.258	.262	14	78.0	.914	.089	.148
401C	55.7	.817	.251	.260	20	86.2	.947	.045	.106
202C	56.4	.820	.232	.256					

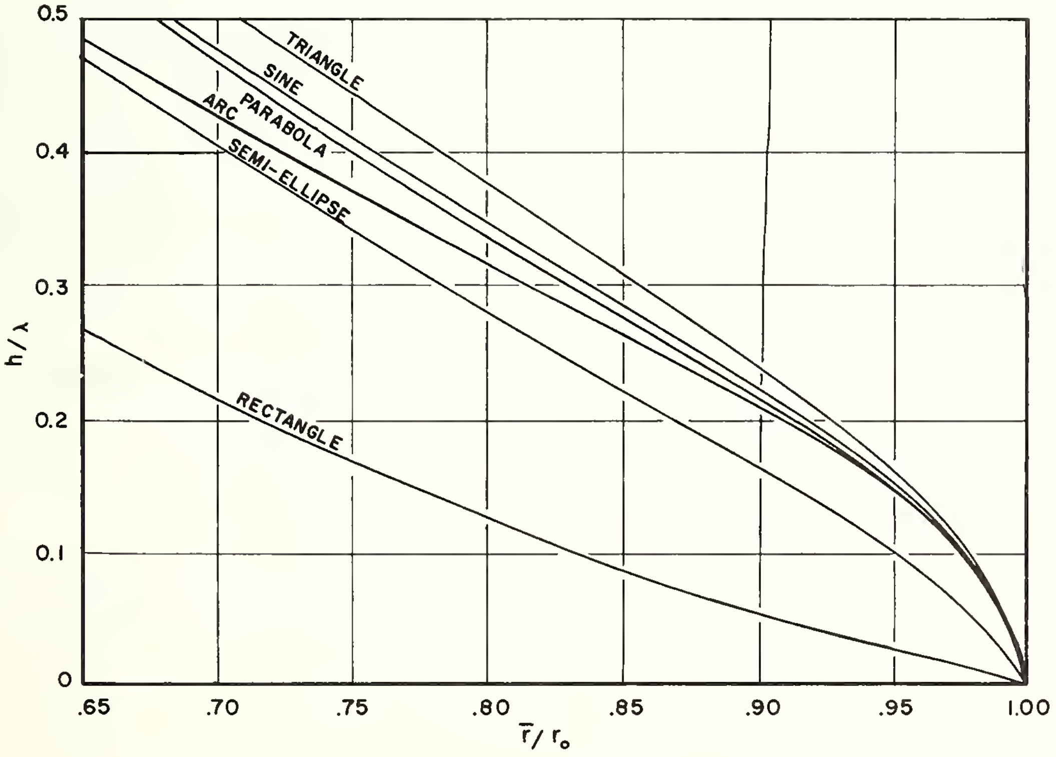


Figure 31.—Calculated shape factor vs. r/r .

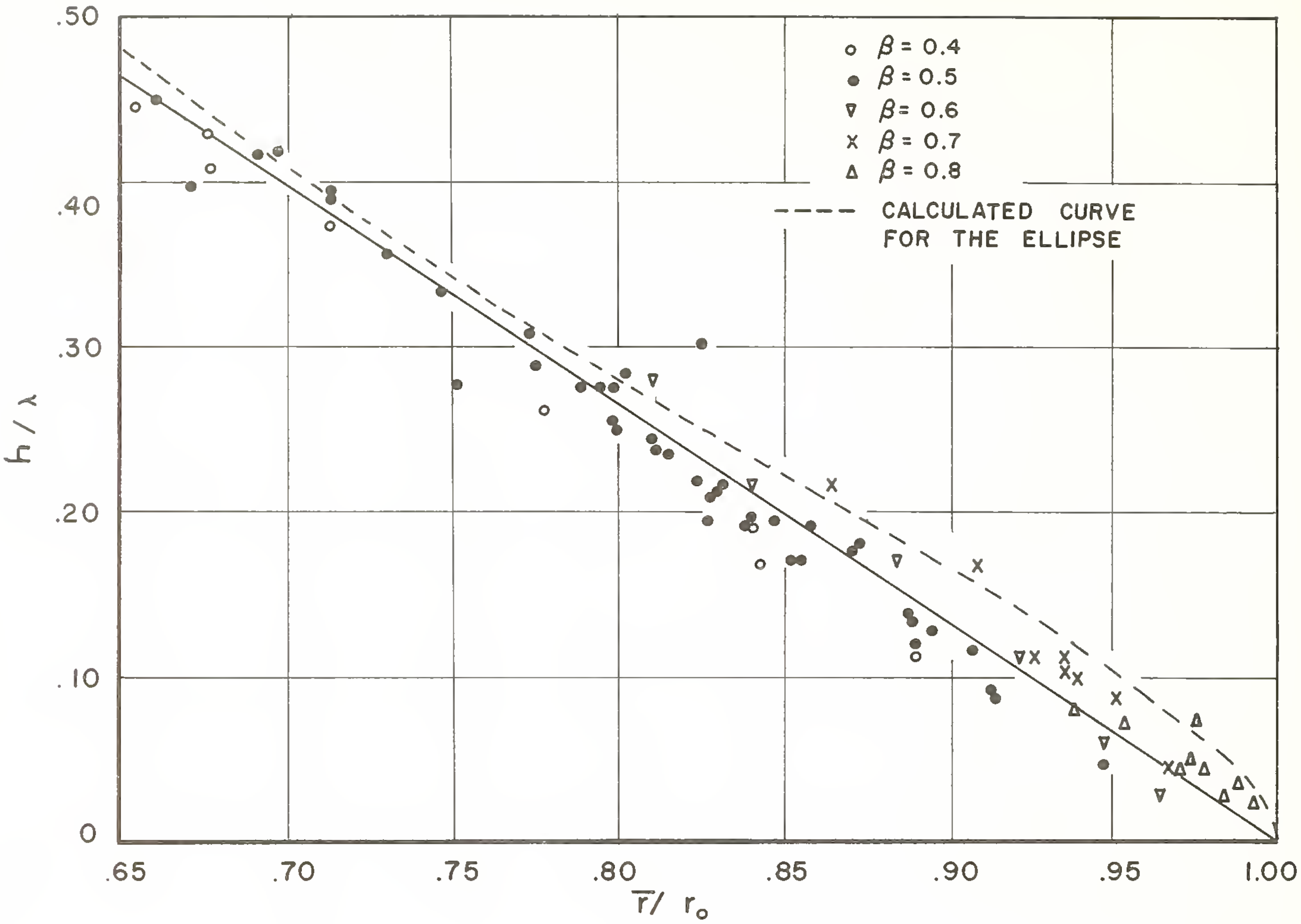


Figure 32.—Measured shape factor vs. r/r .

Figure 33. A steel ruler covers the specimen to be tested, with the end of the ruler matching the end of the specimen. A weight is used to hold the sample down to the platform. The ruler, together with the sample, is gradually extended over the platform. Care is taken so that there is no relative motion between the ruler and the sample. When the overhanging end touches the 43 degree line, measurement is taken from the ruler to see how far it has protruded beyond the edge of the platform. The bending length, c, is taken as one half of this value. This relationship was derived as follows:

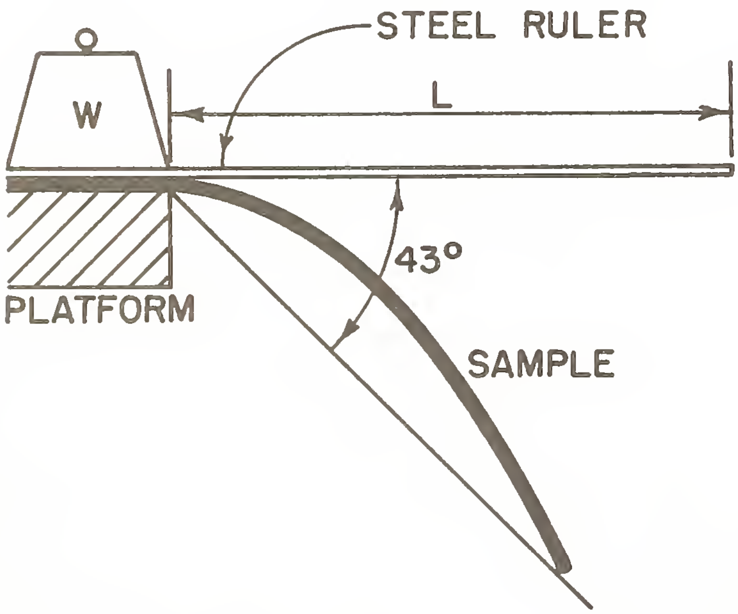


Figure 33.—Strip Bending test.

Peirce defined the bending length as:

$$C = L \left(\frac{\cos 0.5\theta}{8 \tan \theta}\right)^{1/3} \quad \text{------------(94)}$$

where:

L = length of overhang,

θ = chord angle of the deflection curve

If we set $C = \frac{L}{2}$

then:

$$\left[\frac{\cos 0.5\theta}{8 \tan \theta}\right]^{1/3} = 1/2$$

or:

$$\tan\theta = \cos 0.5\theta$$

Solving $\theta = 43°$ (Approx.)

Many fabrics tend to curl and twist when cut into small specimens, and this affects the reproducibility and the physical meaning of the test results. To remedy this, readings are taken for both sides of the fabric and then the test is repeated on the same specimen with the ends reversed. Therefore, the two values of the bending length are obtained on any one specimen from four readings of overhanging length.

The number of samples necessary to give a representative value for the bending length depends upon the regularity of the results and the degree of accuracy demanded. Five in each direction, warp and filling, is a reasonable number.

2. Mean Bending Length

Since drape is partially dependent on fabric stiffness, a good correlation exists between bending length, c, and Drape Coefficient, F. However, F is a unique function of a fabric while c is directional, i.e., c_w and c_f for warp and filling directions respectively. To put F and c on a comparable basis, the two values of c_w and c_f must first be combined into one single mean. Peirce derived the following expression for this mean, c_p:

$$c_p = \sqrt{c_w c_f}\ \frac{1}{2}\left[k + \frac{1}{k}\right] \qquad \text{----------(95)}$$

where:

$$k = \left[\frac{(c_w)}{(c_f)}\right]^{3/4} \qquad \text{--------------(96)}$$

As an approximation, Peirce suggested the geometric mean:

$$c_G = \sqrt{c_w c_f} \qquad \text{-----------------(97)}$$

However, this approximation is not as good as one made with the arithmetical mean:

$$\bar{c} = \frac{1}{2}(c_w + c_f) \qquad \text{--------------(98)}$$

The error involved in using either approximation may be calculated as follows:

Let:

$$\alpha = \frac{c_w}{c_f}\ ;\ \text{then,}\quad k = \alpha^{3/4}$$

Let:

E_G = Error in geometric mean.

Let:

E_A = Error in arithmetical mean.

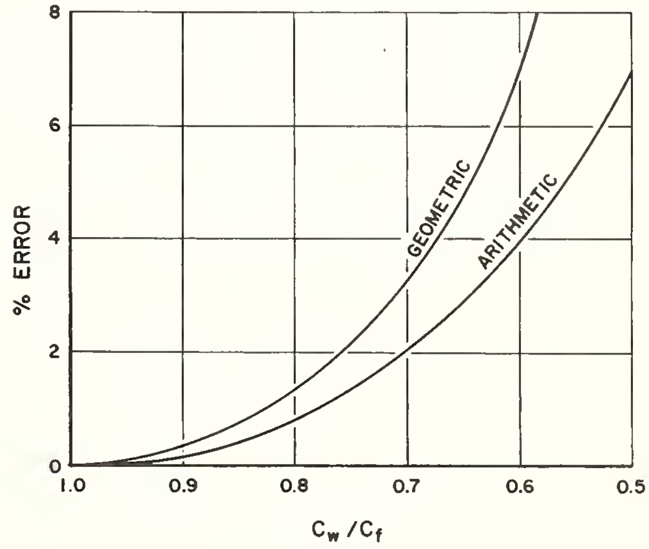
Then:

$$E_G = 1 - \frac{c_G}{c_p} \quad \text{and} \quad E_A = 1 - \frac{\bar{c}}{c_p}$$

$$E_G = 1 - \frac{\sqrt{c_w c_f}}{\sqrt{c_w c_f}\ \frac{1}{2}\left[k + \frac{1}{k}\right]} = 1 - \frac{2k}{k^2 + 1} \qquad \text{-----------(99)}$$

$$E_A = 1 - \frac{c_w + c_f}{c_w c_f\left[k + \frac{1}{k}\right]} = 1 - \frac{(\alpha + 1)\alpha^{1/4}}{\alpha^{3/2} + 1} \qquad \text{------(100)}$$

These errors can be easily calculated for various ratios of c_w / c_f as listed in Table 21 and plotted in Figure 34.



Figures 34.—Errors involved in using geometric and arithmetic approximations for the mean bending length, c_p.

Obviously the arithmetic approximation is more accurate. The arithmetic mean from Figure 34, is accurate within 2% for ratios of c_w / c_f equal to 0.7 or more, for example 0.70 inches x 100 inches, etc. For values of greater difference than these, the exact method must be used.

The solution of the exact equation is greatly simplified by using the chart of Figure 35. The mean value of the bending length may be read

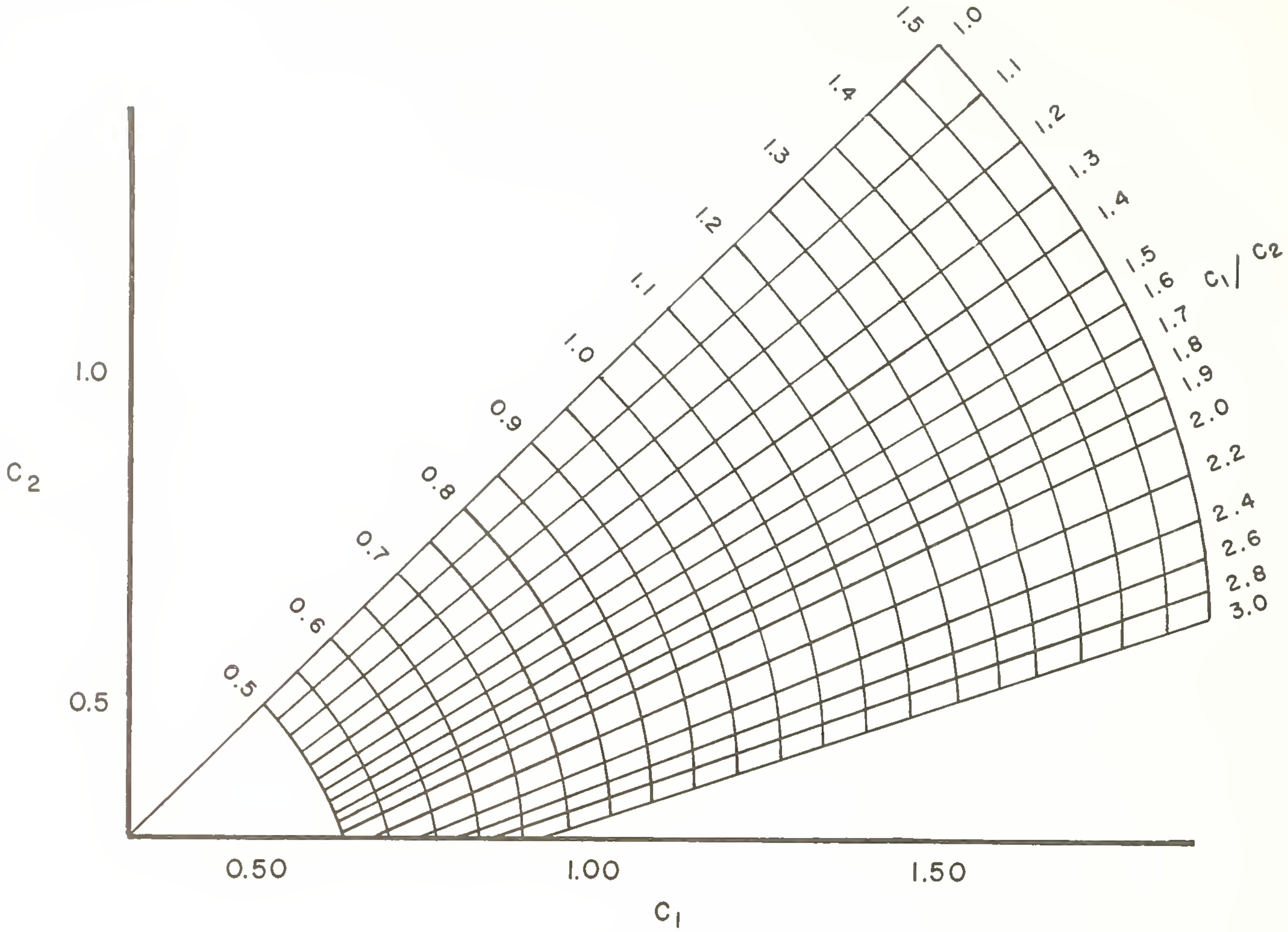


Figure 35.—Mean bending length chart.

directly from the chart where the values of c_1 and c_2 cross.

3. Factors Influencing Fabric Stiffness

Table 21.—*Errors in Bending Lengths by the use of Geometric and Arithmetic Means*

c_w/c_f	E_G	E_A
	Percent	*Percent*
1.00	0.0	0.0
.90	.3	.1
.80	1.4	.7
.70	3.5	1.9
.60	6.9	3.9
.50	12.2	6.8
.40	19.8	11.1
.30	30.5	19.4
.20	45.1	26.3
.10	65.5	40.1
.0	Infinite	Infinite

To better understand the effect of stiffness on drape, a simplified analysis was made to determine the factors influencing the bending length. This analysis involves two assumptions which are:

a. The cross yarns add weight but do not give any assistance to the stiffness of the other set of yarns.

b. The yarns are circular in cross section, and the twist in the fibers does not prevent freedom of motion among the fibers when the yarn bends.

Consider a cantilever strip of length, L, and width, b. The number of threads per inch of fabric in the warp and filling directions are respectively, T_w and T_f. The weights of the yarns per unit length are ρ_w and ρ_f and the moments of inertia of their cross sections about their own axis are I_{ow} and I_{of}.

The bending length, c, is given by F. T. Peirce as:

$$C = \left(\frac{EI}{w}\right)^{1/3} \text{ ---------------- (101)}$$

where:

E = Young's modulus,

I = Moment of inertia of the cross section;

w = Weight of fabric per unit length, if the sample is 1 inch in width.

The object of this analysis is to see what factors in the physical construction of a fabric will alter the value of its bending length. For the sake of simplicity, the direction of the fabric is fixed so that the warp yarns run along the longer dimension of the cantilever strip; i.e., the length of the warp yarn is L and that of the filling, b. A further assumption is made here in neglecting the crimp. Now consider each term in Equation (101).

a. *The modulus, E.* If it is assumed that the cross yarns do not give any assistance toward the stiffness of the strip, then the modulus of the strip is the same as the modulus of the yarns. This means that stiff yarns (high modulus) produce stiff fabrics (larger value of the bending length).

b. *The Moment of inertia, I.* The moment of inertia of a strip is roughly equal to the sum of the moments of inertia of the individual yarns in the strip:

$$I = \sum I_o$$

$$I_w = \sum I_{ow} = I_{ow}\, b\, T_w \quad \text{--------} (102)$$

If the width of the strip, b, is held constant at unity then the moment of inertia varies directly with I_{ow} and T_w. In other words, both larger yarns and tighter weaves result in longer bending lengths (or stiffer fabrics).

c. *The weight of the fabric, w.* The weight of the fabric per unit length (with width, b, equal to 1 inch) is given by the following expression:

$$w = b\left[\rho_w\, T_w + \rho_f\, T_f\right] \quad \text{----} (103)$$

Heavier fabrics are more flexible if the construction is such that there are a few heavy yarns rather than many light ones.

d. *Combined effects.* Equation (100) may be rewritten as follows:

$$c_w = \left[\frac{E(I_{ow} b\ T_w)}{b(\rho_w T_w + \rho_F T_F)}\right]^{1/3} = \left[\frac{E\ I_{ow}\ T_w}{\rho_w T_w + \rho_f\ T_f}\right]^{1/3} \quad \text{----} (104)$$

If it is further assumed that the individual fibers within a yarn are allowed to slip with respect to each other, then the sum of all the moments of inertia of the individual fibers becomes the moment of inertia of the yarn:

$$I_o = n\ \frac{\pi\ (\text{fiber diameter})^4}{64} \quad \text{---} (105)$$

wherein n is the number of fibers in the yarn, assuming the fiber cross section to be round. In a circular yarn, n may be expressed as follows:

$$n \propto \left(\frac{\text{yarn diameter}}{\text{fiber diameter}}\right)^2 \quad \text{---------} (106)$$

Let d be the yarn diameter, then the yarn moment of inertia becomes:

$$I_o \propto \frac{\pi\ d^4}{64\ n} \quad \text{------------------} (107)$$

The weight per unit length of yarn, ρ, is the product of the yarn cross sectional area, $\pi d^2/4$, and the density, σ:

$$\rho = \frac{\pi\ d^2\ \sigma}{4} \quad \text{-------------} (108)$$

Combining (107) and (108):

$$I_o \propto \frac{\rho^2}{4\ \pi\ n\ \sigma^2} \quad \text{-------------} (109)$$

Substituting (106) into (104):

$$c_w \propto \left[\frac{E\rho_w^2\ T_w}{4\ \pi\ n_w\ \sigma_w^2\ (\rho_w T_w + \rho_f T_f)}\right]^{1/3} \quad \text{---------} (110)$$

The weight of the yarns per unit length may be expressed by the denier:

$$\rho = kD \quad \text{----------------------} (111)$$

where:

k = factor to correct denier to weight per unit length, D = Denier.

Substituting (111) into (110):

$$c_w \propto \left[\frac{EkD_w^2 T_w}{4\ \pi\ n_w \sigma_w^2\ (D_w T_w + D_f T_f)}\right]^{1/3} \quad \text{-----------} (112)$$

In comparing fabrics made of different fibers, yarns, and construction, the ratio of the strip bending lengths can be expressed as follows: [The subscripts 1 and 2 denote fabrics No. 1 and No. 2]

$$\frac{c_{w_1}}{c_{w_2}} = \frac{\left[\dfrac{E\,D_w^{\,2}\quad T_w}{n_w\,\sigma_w^{\,2}\quad (D_w T_w + D_f T_f)}\right]_1^{1/3}}{\left[\dfrac{E\,D_w^{\,2}\quad T_w}{n_w\,\sigma_w^{\,2}\quad (D_w T_w + D_f T_f)}\right]_2^{1/3}} \quad \text{-----------} \ (113)$$

Simplifying (113):

$$\frac{c_{w1}}{c_{w2}} = \left(\frac{E_1}{E_2}\right)^{1/3}\left(\frac{D_{w1}}{D_{w2}}\right)^{2/3}\left(\frac{T_{w1}}{T_{w2}}\right)^{1/3}\left(\frac{n_{w2}}{n_{w1}}\right)^{1/3}\left(\frac{\sigma_{w2}}{\sigma_{w1}}\right)^{2/3}$$

$$\frac{(D_wT_w + D_fT_f)_2^{\,1/3}}{(D_wT_w + D_fT_f)_1^{\,1/3}} \quad \text{------------------------} \ (114)$$

Experimental Check

Compare the bending lengths in the warp direction of two plain weave fabrics described below:

	Fabric No. 1	Fabric No. 2
Fiber Type	Acetate	Cotton
Approximate Modulus [20]	23.8 g.p.d.	125 g.p.d.
Threads per inch (wxf)	68 x 48	79 x 80
Yarn Denier (wxf)	300 x 300	183 x 130
No. of filaments per yarn (wxf)	104 x 104	61 x 43
Specific Gravity	1.48	1.33
Bulking Factor	Assume to be the same	
Measured Bending Length (warp)	0.68"	1.07"

[20] Determined from the slope of stress-strain curve.

Substituting into Equation (114):

$$\frac{c_{w1}}{c_{w2}} = \left(\frac{23.8}{125}\right)^{1/3}\left(\frac{300}{183}\right)^{2/3}\left(\frac{68}{79}\right)^{1/3}\left(\frac{61}{104}\right)^{1/3}\left(\frac{1.48}{1.35}\right)^{2/3}\left(\frac{183\text{x}79+130\text{x}80}{300\text{x}68+300\text{x}48}\right)^{1/3}$$

$$\frac{c_{w1}}{c_{w2}} = 0.576 \times 1.390 \times 0.951 \times 0.837 \times 1.074 \times 0.894 = 0.612$$

the experimental ratio of the bending lengths is:

$$\frac{c_{w1}}{c_{w2}} = \frac{0.68}{1.07} = 0.635$$

$$\%\ \text{Error} = \frac{0.635 - 0.612}{0.635} \times 100 = 3.6\%$$

All things being considered, this is a very good check.

4. Paperiness

From Table 3 it is seen that the correlation between the Strip Bending Length and the Drape Coefficient is excellent. One may then ask, if this is the case, why use the Drapemeter, since the strip bending tester is so much simpler to use? The answer to this question is extremely obvious. The strip bending tester measures the bending properties of materials in any one direction. However it falls down when the performance under two dimensional distortion is desired. An example of how the strip bending tester fails is given by a comparison of papers and fabrics with the same strip bending stiffness. Typical results are given in Table 22, where it may be seen that although the bending lengths of the papers and the fabrics are similar, their draping qualities as given by percent F are not, nor are they subjectively classed as being alike.

Table 22.—*Effect of Paperiness as Detected by the Drapemeter*

Material	cs,	F @ $\beta = 0.5$ [1]
	Inches	*Percent*
Tissue paper	0.96 x 1.35	92.8
Thin wax paper	1.21 x 1.21	90.5
Fabric No. 13	1.04 x 1.23	74.1
Fabric No. 12	1.29 x 1.10	73.1

[1] A difference of 5% in the Drape Coefficient is usually detectable by visual inspection.

Similar discrepancies may be observed from the use of the Drape-o-meter.[9] This instrument is reported to be capable of measuring drap-

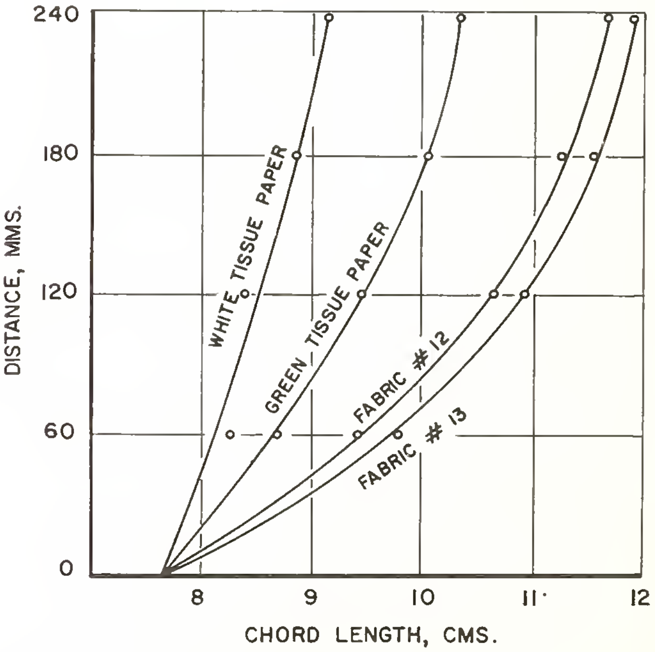


Figure 36.—Drape-o-meter.

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[9] Description and use of the Drape-o-meter are given by Winn, J. L., and Schwarz, E. R., "American Dyestuff Reporter:" P-226-P230, P238. April 28, 1941.

ability. Test results of these samples on the Drape-o-meter (2 papers and 2 fabrics) show that the papers drape better than the fabrics (Fig. 36), while common knowledge indicates this not to be the case.

V. FACTORS WHICH INFLUENCE THE DRAPING PROPERTIES OF COTTON FABRICS.

Sections III and IV of this report describe two of the prime objectives of the research. First, through subjective evaluation it has been shown that the Drapemeter evaluates drapability. Second, the principles of applied mechanics were shown to have been successfully applied, excellent correlation with experimental data having been obtained, thus enabling comparison of results on an intelligent basis.

The work presented in this fifth section involves the drape data and considerations of these data for varying yarn and fabric structures, undertaken in order to determine the geometrical factors which influence the draping properties of cotton cloth.

Unfortunately, cotton fabrics with systematic variations in fabric geometry were commercially unobtainable. Since this research did not involve the manufacture of experimental fabrics, the best alternative was to achieve the objective in two steps, by:

a. Use of a set of available experimental fabrics, woven from acetate yarns, which contained systematic variations in fabric geometry. With these fabrics, it was possible to form some generalized conclusions concerning the effect of structural variations on fabric drapability.

b. Use of some cotton fabrics collected from cooperating manufacturers. Each set of cotton fabrics thus obtained usually varied in only one geometrical parameter as yarn twist, yarn number, weave type and the like. It was then possible to check the generalized conclusions derived from the "model" fabrics (a, above) against the specific case of cotton fabrics.

A. Use of Acetate Models

A series of acetate fabrics designed and woven for study in the "Form Factor Project" was made available to this research at the Fabric Research Laboratories. The Form Factor Project is sponsored by the Office of the Quartermaster General.

These fabrics were made from 300 denier acetate yarns, both in the staple (1½ inch) and continuous filament form. The variations were yarn twist, weave type, and threads per inch as listed in Table 23.

1. Effect of Yarn Twist

The effect of yarn twist upon Drape Coefficient (% F) is shown in Table 24. These values are plotted in Figure 37.

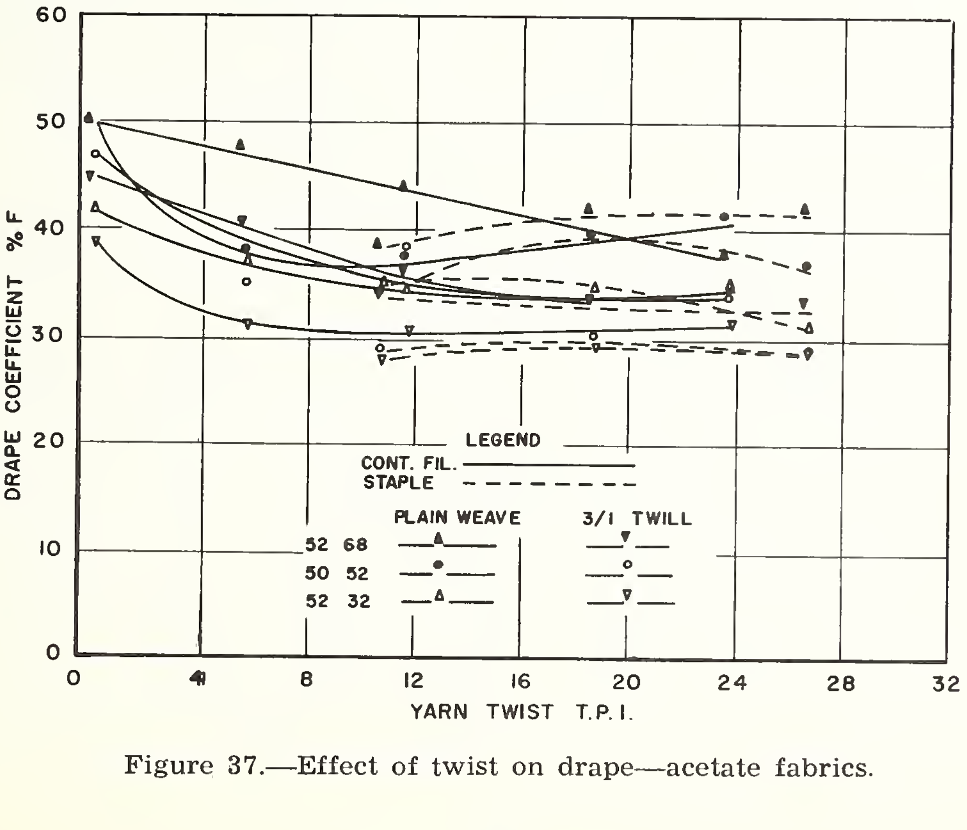

Figure 37.—Effect of twist on drape—acetate fabrics.

Table 23.—*Construction of Office of the Quartermaster General (OQMG) Fabrics Woven from 300 Denier Acetate Yarns*

Variables	Structures Available
Yarn twist, t.p.i.	For 1½" staples: 11, 19, and 27. For Cont. Fils: 0.3, 6, 12, and 24.
Texture, yarns per inch	52 x 58, 50 x 52, and 52 x 32.
Weave type	Plain, 2/2 basket [1], and 3/1 twill.

[1] Not tested.

There are apparently greater differences in drapability resulting from variation in yarn twist among the continuous filament fabrics than from such variation among the staple yarn fabrics. However, it should be remembered that the ranges of twists for the two sets of samples are not the same. The continuous filament yarns varied from 0.3 to 24.0 t.p.i., but the range for the staple yarns varied from 11.0 to 27.0 t.p.i. The differences in Drape Coefficients for the same twist ranges (viz. 11.0 to 24.0 t.p.i.) of the two sets of curves are approximately the same.

For the range of twists studied, the curves in Figure 37 show improved drapability (decrease of Drape Coefficient) with the increase in yarn twist. The phenomenon, with the exception of one fabric, occurs within the lower twist region, i.e., from 0.3 to 12.0 t.p.i. The changes, if any, from 12.0 to 27.0 t.p.i. are very small.

Table 23 gives the average Drape Coefficients of fabrics of the two weaves and the three yarn textures woven from yarns of the same twist, each average value being the mean of six fabrics. The relationship between drapability and yarn twist is plotted as an average in Figure 38.

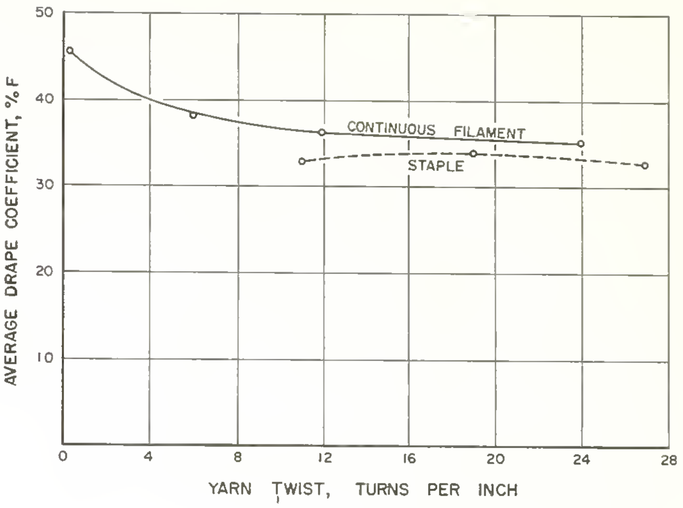

Figure 38.—Effect of twist on drape — average curves for acetate fabrics.

Since the samples were not of the same weave and texture, it is doubtful whether the averaging is analytically valid. Nevertheless the "average curve" serves to indicate the trend of how drapability varies with yarn twist. The Drape Coefficient decreases substantially between 0.3 t.p.i. and 6.0 t.p.i., a somewhat lesser decrease occurs between 6.0 t.p.i. and 12.0 t.p.i., and thereafter it remains constant.

From an analytical point of view, the effects of yarn twist on drapability are largely due to alterations in yarn geometry These are changes in bulking factor and ellipticity. Bulking factor is an indication of how tightly the fibers are packed within a yarn. Ellipticity measures the

Table 24.—*Effect of Yarn Twist on the Drapability of OQMG Acetate Fabrics*

Weaves, by Thread Count	Drape Coefficient, F at $\beta = 0.5$ [1] with						
	Yarn Twist (turn per inch) of—						
	0.3 [2]	6 [2]	11 [3]	12 [2]	19 [3]	24 [2]	27 [3]
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
52 x 68:							
Plain weave	49.7	47.1	37.8	43.3	41.1	36.7	40.9
3/ twill	44.6	40.0	33.5	35.4	32.9	33.7	32.3
50 x 52:							
Plain weave	49.8	37.5	33.2	36.8	38.6	40.5	35.8
3/1 twill	46.8	34.6	28.3	37.8	29.3	33.2	27.9
52 x 32:							
Plain weave	41.7	36.8	34.4	34.1	33.6	34.3	30.3
3/1 twill	38.5	30.8	27.6	30.3	38.6	30.9	28.1
Average [4]	45.2	37.8	32.5	36.3	34.0	34.9	32.6

[1] Some tests were performed at $\beta = 0.6$, data converted.
[2] Continuous filament yarns, 300 denier.
[3] 1½" staple filament yarns, 300 denier.
[4] See text for explanation.

deviations from roundness of the yarn cross section. Each of these factors can either improve or impair drapability. Table 25 lists such causes and effects.

Table 25.—*Theoretical Effects of Yarn Twist on Fabric Drapability*

Factors Altered by Increase in Yarn Twist	Influence on Fabric Drapability
I. **Bulking Factor:** Reduction in bulk reduces yarn cross section area, which:	
(a) Restricts fiber slippage.	Impairment
(b) Reduces the moment of inertia.	Improvement
II. **Ellipticity:** Increase in roundness of yarns:	
(a) Reduces cover factor, facilitates greater freedom for relative (trellislike) yarn motion,	Improvement
(b) Increases the moment of inertia (if cross sectional area remains unchanged).	Impairment

Measurements were made of the acetate fabrics cross section by means of camera lucida drawings. The results showed that both the bulking factor and ellipticity varied with yarn twist as postulated; however, the effect of yarn twist changes occurred predominantly in the low twist region. Little or no effect was observed for twists higher than 12.0 turns per inch. This finding further substantiates the experimental results, and explains the relative insensitivity of the staple fiber fabrics to yarn twist variations.

2. Effect of Weave Type

Referring to Table 24, it can be clearly seen that the 3/1 twill fabrics drape better than the plain weave fabrics, because of the following reasons:

a. The longer floats in the 3/1 twill weave enable the yarns to remain in a relatively flat plane. Thus the cross sectional moment of inertia of the fabric may be lessened, thereby reducing the stiffness. (See Table 25).
b. The longer floats also provide less pressure at the crossovers of the warp and filling yarns, facilitating thereby distortion of the fabric structures.

It is presumed that the 2/2 basket-weave fabrics (not tested) will perform somewhere between the 3/1 twill and the plain weave. Data on 2/2 basket cotton fabrics are given in another section of this report.

3. Effect of Thread Count

Table 26 lists the Drape Coefficients of the two extremes of the thread count within this group of fabrics (i.e., 52 x 68 and 52 x 32).

Table 26.—*Effect of Thread Count on the Drapability of OQMG Acetate Fabrics* [1]

Thread Count and Weaves		Drape coefficient, F at $\beta = 0.5$ with Thread Count (yarns per inch) of	
		52 x 68	52 x 32
		Percent	*Percent*
0.3 t.p.i.	plain weave	49.7	41.7
	3/1 twill	44.6	38.5
6.0 t.p.i.	plain weave	47.1	36.8
	3/1 twill	40.0	30.8
11 t.p.i.	plain weave	37.8	34.4
	3/1 twill	33.5	27.6
12 t.p.i.	plain weave	43.3	34.1
	3/1 twill	35.4	30.3
19 t.p.i.	plain weave	41.1	33.6
	3/1 twill	32.9	28.6
24 t.p.i.	plain weave	36.7	34.3
	3/ twill	33.7	30.0
27 t.p.i.	plain weave	40.9	30.3
	3/1 twill	32.3	28.1

[1] Rearranged data from Table 24.

The differences in Drape Coefficients between 52 x 68 fabrics and 52 x 32 fabrics ranged from 2.4% to 10.6% (average difference = 7.1%). These differences were found to be statistically significant.

This observation coincides with the theoretical analysis mentioned earlier in this report (Section IV-E). It was postulated that everything else being equal, the stiffness of a fabric increases with the texture. The following check is made to verify this assumption.

Consider two fabrics whose actual thread counts are 57.7 x 32.8 and 75.9 x 52.3, whose measured bending lengths are 0.73 x 0.51 inches and 0.69 x 0.57 inches, respectively.

Simplifying Equation (114), the ratios of the bending lengths of the two fabrics for both warp, t_w , and filling, c_f, may be calculated as follows:

$$\frac{c_{w1}}{c_{w2}} = \left(\frac{t_{w1}}{t_{w2}} \times \frac{t_{w2} + t_{f2}}{t_{w1} + t_{f1}} \right)^{1/3}$$

and:

$$\frac{c_{f1}}{c_{f2}} = \left(\frac{t_{f1}}{t_{f2}} \times \frac{t_{w2} + t_{f2}}{t_{w1} + t_{f1}} \right)^{1/3}$$

then:

$$\frac{c_{w1}}{c_{w2}} = \left(\frac{57.7}{75.9} \times \frac{75.9 + 52.3}{57.7 + 32.8} \right)^{1/3} = 1.03$$

and:

$$\frac{c_{f1}}{c_{f2}} = \left(\frac{32.8}{52.3} \times \frac{75.9 + 52.3}{57.7 + 32.8} \right)^{1/3} = 0.96$$

The actual ratios of the measured values are as follows:

$$\frac{c_{w1}}{c_{w2}} = \frac{0.73}{0.69} = 1.06$$

and:

$$\frac{c_{f1}}{c_{f2}} = \frac{0.51}{0.57} = 0.90$$

Considering the numerous assumptions made in deriving the above relationships, the result of the experimental check may be considered reasonable. Note that the calculations above give the relative bending lengths of the two fabrics. The stiffness of each fabric is found by multiplying the cube of the bending length by the weight per unit area. Obviously, the stiffness of 57.7 x 32.8 fabric is considerably less than that of the 75.9 x 52.3 fabric.

B. Effect of Staple Length

Of the 42 Quartermaster Form Factor acetate fabrics tested, 18 were woven from 1½ inches cut staple fibers and the other 24 from continuous filaments. Although this number of fabrics is insufficient to form the basis for a complete specification of the effects of staple length, a few generalized comments can still be made. Since staple fibers depend upon friction and twist to be translated into a continuous yarn, with the amount of friction being a function of the twist, it is reasonable to assume that as a result some degree of freedom of relative motion the staple yarns are not as rigid as continuous filament yarns.

The average curves of Figure 39 show the effect of twist on both the staple fabrics and the continuous filament fabrics. The staple fabrics seemed to drape somewhat better (lower Drape Coefficients) than the continuous filament ones. The difference between these two curves may or may not be of practical or statistical significance; nevertheless, the trend is indicated. Hence, by extrapolation, it might be true that because of more relative fiber slippage and a lack of continuity, extremely short staples will make more drapable fabrics. However, this effect cannot be large, for practical reasons. The number of nonthroughgoing fibers between yarn crossovers in a woven fabric would be few, since even short staple lengths are relatively long compared to the distance between adjacent yarn crossovers in most commercial fabrics.

C. Cotton Fabrics

It has been mentioned previously that direct determination of the factors which influence the draping properties of cotton fabrics is impossible, owing to the lack of sample availability. Under such circumstances, without resorting to large scale weaving of experimental cotton fabrics, certain general principles might be formulated through the use of "model" fabrics made of other fibers. This was done with acetate, as described in Part A of this section. From the few cotton fabrics collected through commercial sources and tested, it has been possible to spot check the findings on acetate, and it is shown that generally these findings apply to cotton.

1. Effect of Yarn Twist

Tables 27 and 28 list two groups of plain weave cotton fabrics which varied primarily

Table 27.—*Effect on Several Factors; Especially Yarn Twist, by Warp Sizing of Plain Weave Cotton Fabrics* [1]

Factor and Sizing Condition		Measurement of Fabrics Nos. 49	50	51
A. Before Desizing:				
Threads per inch	Number	80 x 80	81 x 79	81 x 80
Yarn twist	t.p.i.	23 x 25	26 x 21	29 x 22
Yarns	Number	29 x 41	29 x 38	30 x 39
Weight	Oz./sq.yd.	3.63	3.63	3.63
F at $\beta = 0.5$	Percent	78.3	72.8	72.9
B. After Desizing:				
Threads per inch	Number	79 x 80	80 x 83	79 x 83
Weight	Oz./sq.yd.	3.46	3.55	3.55
F at $\beta = 0.5$	Percent	52.7	51.7	49.9

[1] Samples supplied by R. J. Cheatham of Southern Utilization Research and Development Division.

Table 28.—*Effect on Several Factors, Especially Yarn Twist, by Warp Sizing of Plain Weave Cotton Fabrics* [1]

Factor		Measurement of Fabrics Nos. 62	49	66
Threads per inch	Number	79 x 80	80 x 80	79 x 79
Yarn twist	t.p.i.	19 x 20	23 x 25	27 x 25
Yarns	Number	26 x 36	29 x 41	27 x 39
Weight	Oz/sq.yd.	3.73	3.63	3.73
F at $\beta = 0.5$	Percent	77.2	78.3	78.8

[1] Sample sources: No. 62, Joanna Mills; No. 49, Southern Utilization Research and Development Division; and No. 66, Spartan Mills. Note: Mention of companies in this report does not constitute endorsement by the U. S. Department of Agriculture over other firms not mentioned.

in yarn twist. Since these fabrics were not woven especially for experimental use, not all the other structural factors were held constant. Hence the data can be regarded only in the light of trends.

The three fabrics listed in Table 27 vary in both yarn number and yarn twist. (The effect of yarn number is shown in a subsequent section). The Drape Coefficients of these fabrics were compared statistically:

	Before Desizing	After Desizing
No. 49 and No. 50	Significantly different	Not signif. different
No. 49 and No. 51	Significantly different	Significantly different
No. 50 and No. 51	Not signif. different	Significantly different

The pair that consistently exhibit significant differences is No. 49 and No. 51. This difference is probably real, i.e., due to structure. The other differences shown might be attributed to the effects of sizing, which will be discussed in more detail later. Assuming that the differences in yarn numbers of fabrics No. 49 and No. 51, (29 x 41 vs. 30 x 39) are negligible, then the difference in drapability may be caused by the differences in yarn twists of the two fabrics (23 x 25 vs. 20 x 22 t.p.i.).

Although there is no experimental evidence, at this time, which will permit analysis of the entire range of yarn twist in cotton fabrics, it is possible to speculate what the effects will be on drapability. Since cotton is a staple fiber depending on friction and twist to hold the fibers in yarn form (this is particularly so in the low twist region), the relationship of drapability to twist for cotton depends upon a slightly different mechanism than it does for the continuous filament yarns of acetate, discussed in Part A of this section. Consider the hypothetical relationship given by Figure 39.

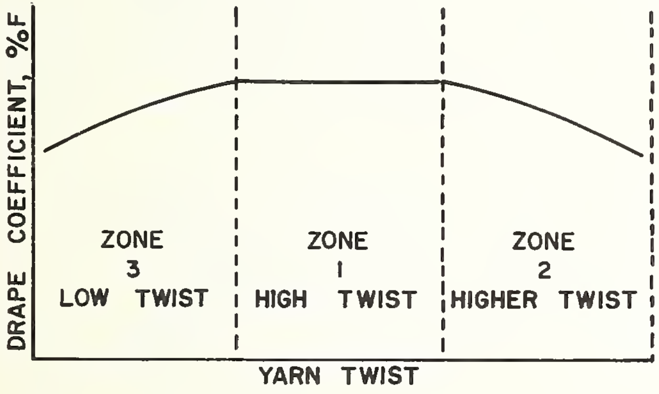

Figure 39.—Postulated effect of yarn twist on fabric drapability.

2. Effect of Weave Type

The samples employed in this study were donated through the cooperation of the Fieldcrest Mills.[10] The 18 cotton fabrics tested were woven into 6 different constructions, and each construction was submitted in 3 different stages of finish. Table 29 lists their constructions and the results of the drape tests. The Drape Coefficients given are averaged from 10 tests, i. e., 5 samples tested both front and back. The samples were 10 inches in diameter, and they were tested on 5-inch supports.

Zone 1. Data show that in the region of high twist, Drape Coefficient is constant with yarn twist.

Zone 2. In the region of very high twist, such as for Fabric No. 51, which has a twist multiplier of 5.80, the drapability is improved by increase in twist.

Zone 3. At the other extreme, i.e., the low-twist end of the spectrum, yarns are apt to be more flexible because of greater freedom of relative fiber motion and of flattening.

Table 28 gives Drapemeter data for three fabrics made by separate manufacturers. If the differences in yarn numbers are again ignored, then the resulting variation, if any, is due to yarn twist. However, statistical analyses revealed the following:

Between No. 49 and No. 62	No significant difference
Between No. 49 and No. 66	No significant difference
Between No. 62 and No. 66	No significant difference

Here again, with respect to the two sets of data in Tables 27 and 28, the lack of differences in drapability with change in yarn twist might be the result of the high twists of these yarns. It has already been shown for both filamentous and staple acetate fabrics that there is no appreciable change in percent F with twist in the higher twist region.

These data were subjected to statistical analyses to evaluate the significance of differences between the drapabilities of the samples. Table 30 lists the pairs of fabrics compared and the statistical conclusions. Where there were significant differences at the 1% level the letter "D" was assigned. If the difference existed at a lower statistical level (5%) then the letter "d" was used. The letter "S" was used to represent the case of no significant difference being found.

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[10] Mention of companies in this report does not constitute endorsement by the U. S. Department of Agriculture over other firms not mentioned.

Table 29.—*Effect of Weave Type on the Drapability of Cotton Fabrics*

GREIGE GOODS STATE

Fabric No.	Weave Type	Texture	Weight	Thickness	F
		Threads/in.	*Oz./sq.yd.*	*Mils*	*Percent*
67	Crow foot	88 x 89	4.36	14.4	85.1
68	Ric-rac	88 x 91	4.42	16.7	84.0
69	2/2 Twill	88 x 90	4.49	13.8	88.3
70	3/1 Twill	88 x 90	4.44	14.8	82.0
71	2/2 Basket	88 x 90	4.40	13.6	88.5
72	Plain weave	88 x 92	4.43	10.9	92.6
	BLEACHED STATE				
73	Crow foot	94 x 85	3.71	8.4	57.2
74	Ric-rac	94 x 86	3.72	8.7	58.6
75	2/2 Twill	94 x 86	3.76	8.5	60.6
76	3/1 Twill	94 x 85	3.86	8.8	58.1
77	2/2 Basket	94 x 88	3.75	8.3	60.8
78	Plain weave	94 x 86	3.82	7.3	72.0
	BLEACHED AND STARCHED				
79	Crow foot	95 x 86	3.78	9.6	54.2
80	Ric-rac	95 x 88	3.80	9.9	51.6
81	2/2 Twill	95 x 84	3.81	9.3	58.7
82	3/1 Twill	95 x 84	3.84	8.8	55.3
83	2/2 Basket	95 x 89	3.75	8.6	54.7
84	Plain weave	95 x 82	3.79	7.1	71.9

[1] Averaged from 10 tests (10" samples, $\beta = 0.5$).

Table 30.—*Summary of Drapability Statistical Significance Tests*[1]

Fabric and Drapability No.

67 vs. 68—S
67 vs. 69—S
67 vs. 70—S
67 vs. 71—S
67 vs. 72—D
67 vs. 79—D

68 vs. 69—S
68 vs. 70—S
68 vs. 71—S
68 vs. 72—D
68 vs. 74—D
68 vs. 80—D

69 vs. 70—D
69 vs. 71—S
69 vs. 72—D
69 vs. 75—D
69 vs. 81—D

70 vs. 71—D
70 vs. 72—D
70 vs. 76—D
70 vs. 82—D

71 vs. 72—D
71 vs. 77—D
71 vs. 83—D

72 vs. 78—D
72 vs. 84—D

73 vs. 74—S
73 vs. 75—D
73 vs. 76—S
73 vs. 77—S
73 vs. 78—D
73 vs. 79—d

74 vs. 75—d
74 vs. 76—S
74 vs. 77—d
74 vs. 78—D
74 vs. 80—D

75 vs. 76—D
75 vs. 77—S
75 vs. 78—D
75 vs. 81—D

76 vs. 77—D
76 vs. 78—D
76 vs. 82—D

77 vs. 78—D
77 vs. 83—D

78 vs. 84—S

79 vs. 80—D
79 vs. 81—D
79 vs. 82—S
79 vs. 83—S
79 vs. 84—D

80 vs. 81—D
80 vs. 82—D
80 vs. 83—D
80 vs. 84—D

81 vs. 82—D
81 vs. 83—D
81 vs. 84—D

82 vs. 83—S
82 vs. 84—D

83 vs. 84—D

[1] Numbers listed are fabric numbers. Comparative drapabilities of any 2 fabrics are represented by the following letters: D = Significant statistical difference at the 1% level; d = Significant statistical difference at the 5% level; and S = No significant statistical difference.

A careful study of Tables 29 and 30 yielded the following observations:

a. The greige fabrics exhibited the least drapability. Corresponding fabrics, of the same weave, in the bleached and the bleached and starched states showed significant improvements in drape. The average difference in Drape Coefficient between the greige and the bleached states was 25%. The average difference in Drape Coefficient between the greige and the bleached and starched was 29%.

The poorer drapability in the greige goods can be largely attributed to the warp sizing (about 15% by weight). In addition to the direct action of the starch, the data show that as a result of desizing and bleaching, the fabric becomes thinner, probably resulting in a decrease in cross sectional moment of inertia, favorable to drape performance. Too, there has been marked change in fabric geometry from a roughly square to a definitely unbalanced construction. The warp yarns per inch have increased, indicating a fillingwise contraction. The filling threads per inch have decreased, indicating some type of warpwise extension and slippage. The concomitant physical effects of these changes are considered, along with those noted below in the discussion of the effect of starching after bleaching, in an effort to refine the general conclusions tabulated in a subsequent section.

b. Fabrics bleached and then starched exhibited improved drapability when compared to the samples which were bleached only. This was true in all cases except for the plain weave, which seemed indifferent to the additional finishing operation. The average reduction in Drape Coefficient was roughly 4% when starching followed bleaching.

These results are apparently a contradiction of experience. Ordinarily, the addition of starch stiffens a fabric and impairs drapability. Actually, the reasons for the improved drape performance, noted in Table 31, of bleached and starched fabrics over those just bleached have not been satisfactorily explained. It is apparent from the changes in weight of the fabric in passing from the bleached to the bleached-starch state that very little starch has been added.

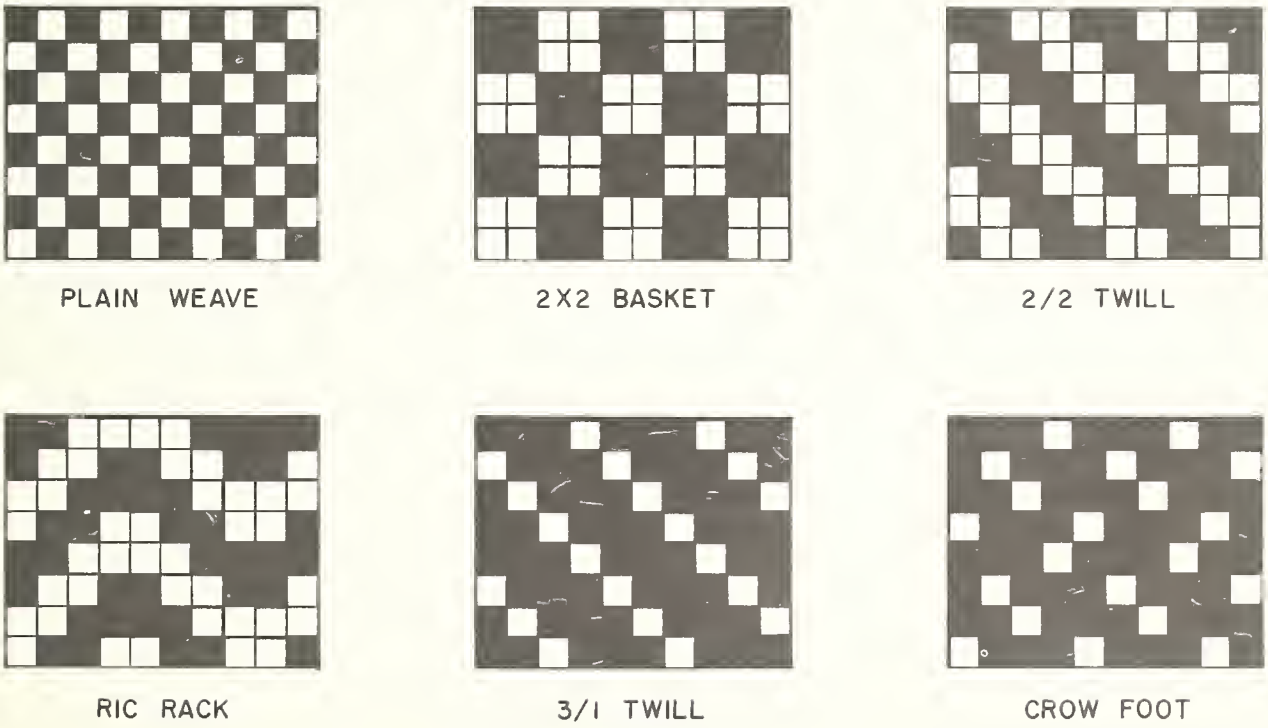
Table 31.—*Drapability Rankings of Weave Types According to Condition of Fabric*

Weave Type	Greige		Bleached		Bleached & Starched	
	Fabric	% F	Fabric	% F	Fabric	% F
MUCH BETTER THAN PLAIN WEAVE						
Ric-rac	No. 68	84.0	No. 74	58.6	No. 80	51.6
3/1 Twill	No. 70	82.0	No. 76	58.1	No. 82	55.3
Crow foot	No. 67	85.1	No. 73	57.2	No. 79	54.2
BETTER THAN PLAIN WEAVE						
2/2 Basket	No. 71	88.5	No. 77	60.8	No. 83	54.7
2/2 Twill	No. 69	88.3	No. 75	60.6	No. 81	58.7
Plain Weave	No. 72	92.6	No. 78	72.0	No. 84	71.9

Whether such a slight amount of starch can either stiffen a fabric or increase its weight enough to significantly influence drape is doubtful. Conceivably, the starch, either directly or in combination with the method of application, induces a geometric influence favorable to drape. For example, the starch may cause a smooth, hard finish on the yarns, increasing yarn mobility and enhancing trellising. Too, the starch may minimize the nesting of twist at crossovers. Both of these factors would improve drape by **decreasing** resistance to yarn movement under the conditions of low stress low strain which exist in a fabric during draping. It may also be noted from Table 29, that a very slight increase in fillingwise yarn shrinkage or fillingwise yarn contraction occurs during starching, as evidenced by an increase in warp thread count from 94 to 95 per inch. Warpwise shrinkage or contraction has also taken place, but in a less consistent direction. Shrinkage and contraction, both fillingwise and warpwise, must however, affect crimp and possibly the ease of yarn buckling; the later would probably improve drape.

c. The relative merits of the various weaves are apparent from the data of Tables 29 and 30. In Table 31, the fabrics are ranked in three groups of descending drapability. The three twills at the top of the table are considered to be much better than the plain weave. No statistically significant differences were found among these three weaves (ric-rac, 3/1 twill, and crow foot) in either the greige or bleached states, although in the bleached and starched state the ric-rac weave draped significantly better than the other two. The 2/2 basket and the 2/2 twill fabrics were statistically similar in each state except the bleached-starched one. These two types did not drape as well as the first three, but they were still superior to the least drapable type of fabric, the plain weave.

Figure 40 is a series of schematic diagrams of the various weave patterns. It appears reasonable to assume that,


PLAIN WEAVE

2X2 BASKET

2/2 TWILL

RIC RACK

3/I TWILL

CROW FOOT

Figure 40.—Various weave types.

everything else being equal (i.e., yarn size, picks and ends, etc.) any differences in drape would most likely be caused by the tightness of the particular weave, since tightness controls the mobility of the yarns. In any fabric structure, the yarns are interlaced to each other by "crossovers." The length of yarns in one direction (say warp) which goes over or under the yarns in the other direction (say filling) for each "crossover" is called the "float length." Hence, for a given number of threads per inch, the longer the float length the fewer the crossovers the looser the structure. For the six weave types studied, the float lengths varied from 1/N to 4/N inches (N being the number of threads per inch). Table 32 shows the distribution and the averages of the float lengths in these structures. It is not at all surprising to find that the ranking of the three fabric groups in float length coincides with the ranking of drapability.

Table 32.—*Float Lengths of Various Weaves*

Weave Type[1]	Percent of Total 1/N	2/N	3/N	4/N	Average
Ric-rac	--------	75%[2]	--------	25%[2]	2.5/N
3/1 Twill	25%	--------	75%	--------	2.5/N
Crow Foot	25%	--------	75%	--------	2.5/N
2/2 Basket	--------	100%	--------	--------	2.0/N
2/2 Twill	--------	100%	--------	--------	2.0/N
Plain weave	100%	--------	--------	--------	1.0/N

[1] Descending order of rank.
[2] For equal numbers of warp and filling threads per inch.

3. Effect of Thread Count

The samples used in this study were contributed by the Joanna Cotton Mills.[11] These results of the Drapemeter tests on these fabrics are tabulated in Table 33. If the variations in yarn twist and yarn number are assumed negligible in their effects within these samples, then the data confirm the findings mentioned earlier of improved drapability with lower texture. Concerning drapability, statistical analyses show:

Fabrics Compared	Before Desizing	Siynificantly different
No. 62 and No. 63	Significantly different	Siynificantly different
No. 63 and No. 64	Significantly different	Siynificantly different
No. 63 and No. 65	Significantly different	Not signif. different
No. 64 and No. 65	Not signif. different	After Desizing

Table 33.—*Effect of Texture and Sizing on Plain Weave Cotton Fabrics*[1]

Factor and Sizing Condition	Measurement of Fabric Nos 62	63	64	65
A. Before Desizing:				
Threads per inch ......Number	79 x 80	62 x 60	60 x 49	57 x 52
Yarn twist, ...t.p.i.	19 x 20	20 x 24	19 x 20	20 x 24
Yarns ....Number	26 x 36	27 x 42	26 x 41	25 x 41
Weight ....Oz./sq. yd.....	3.73	2.89	2.49	2.45
F @ $\beta = 0.5$ ....Percent ...	77.2	71.4	65.7	67.2
B. After Desizing:				
Threads per inch ....Number	83 x 80	66 x 64	63 x 53	58 x 52
Weight ....Oz./sq./yd...	3.41	2.84	2.43	2.34
F @ $\beta = 0.5$ ....Percent....	54.0	45.3	42.6	42.1

[1] Samples supplied by Joanna Cotton Mills. Note. Mention of companies in this report does not constitute endorsement by the U. S Department of Agriculture over other firms not mentioned.

Since the textures of No. 64 and No. 65 are not very different, and the total number of threads in a square inch are identical, it is not surprising to find comparable drapabilities for the two fabrics.

4. Effect of Yarn Diameter

Table 34 lists the construction and Drape Coefficients of cotton fabrics woven from yarns of different numbers. In essence, the data show two weave types, the 3/1 twill and the oxford, each woven with two different sets of yarns, both in the greige as well as in the bleached state. When two fabrics, with the same weave type and texture, are compared, the one woven from coarser yarns always has poorer drape (i.e., higher value of Drape Coefficient). The differences in Drape Coefficients between fabrics numbered 87, 89, 88, 90, 93, 95, 94 and 96 are all statistically significant.

Table 34.—*Effect of Yarn Diameter on the Drapability of Cotton Fabrics*

Fabric No. and Construction	Yarns *Number*	F[1] *Percent*
3/1 Twill 100 x 60 threads/in.:		
No. 87 (greige)	40s warp x 42s filling	65.0
No. 89 (greige)	31s warp x 32s filling	69.7
No. 88 (white)	40s warp x 42s filling	51.7
No. 90 (white)	31s warp x 32s filling	57.5
Oxford 88 x 42 threads/in.:		
No. 93 (greige)	40s warp x 42s filling	64.2
No. 95 (greige)	40s warp x 15s filling	79.6
No. 94 (white)	40s warp v 42s filling	54.4
No. 96 (white)	40s warp x 15s filling	65.8

[1] Averaged from 10 tests (10" samples, $\beta = 0.5$). Differences in Drape Coefficients between fabric numbers 87 & 89, 88 & 90, 93 & 95, and 94 & 96 are all statistically significant.

5. Effect of Fiber Maturity

Two cotton fabrics identical in construction, for all practical purposes, but different in fiber maturity were tested on the Drapemeter. These samples were furnished by the Southern Regional Research Laboratory. The results of fabric analyses and drape tests are given in Table 35. The Drape Coefficients (10 inch samples with $\beta = 0.5$) of the two samples were 52.6% for the immature, and 60.9% for the mature. The difference of 8.3% in the Drape Coefficient was not only statistically significant but also very noticeable during visual inspection.

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[11] Mention of companies in this report does not contribute endorsement by the U. S. Department of Agriculture over other firms not mentioned.

Table 35.—*Effect of Structure on Drapability of Fabrics Woven From Mature and Immature Cotton Fibers*

Fabric	No. 85—Immature	No. 86—Mature
Fiber Name	"Sike"	Deltapine
Fiber maturity .... Percent	28	86
Staple length .... Inches	1-1/16	1-1/16
Warp yarn	2-ply 21s	2-ply 20s
Filling yarn	2-ply 21s	2-ply 20s
Thread count .... Number	47 x 50	46 x 50
Fabric Weight .... Oz./sq. yd.	3.22	3.24
Fabric thickness .... Inches	0.0132	0.0130
Drape Coefficient, F[1] .... Percent	56.6	60.9

[1] Averages from 10 tests. (10″ samples $\beta = 0.5$). Yarn twists and finishing processes were said to be identical.

The superior performance in drapability of the immature sample was probably due to the combined effects of lower fiber modulus and finer fiber cross section. Figure 41 shows the load-elongation curves of the warp yarns removed from the two fabrics. Since both curves were essentially linear, it was relatively simple to compare the respective moduli. The modulus of the mature fiber yarn was considerably higher than that containing immature fibers. Photomicrographs of the fiber cross sections are given in Figure 42 and of the yarn cross section in Figure 43. It is very evident that the immature fibers are much finer than the mature ones.

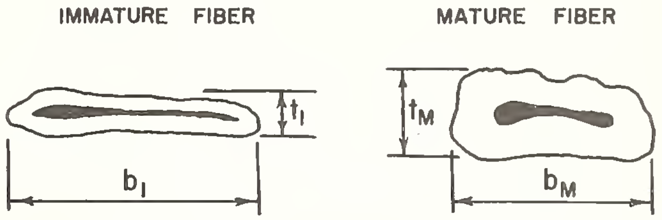


Figure 42.—Cross sections of cotton fabrics.

Referring again to Figure 41, it is reasonable to estimate that the ratio of the moduli of the

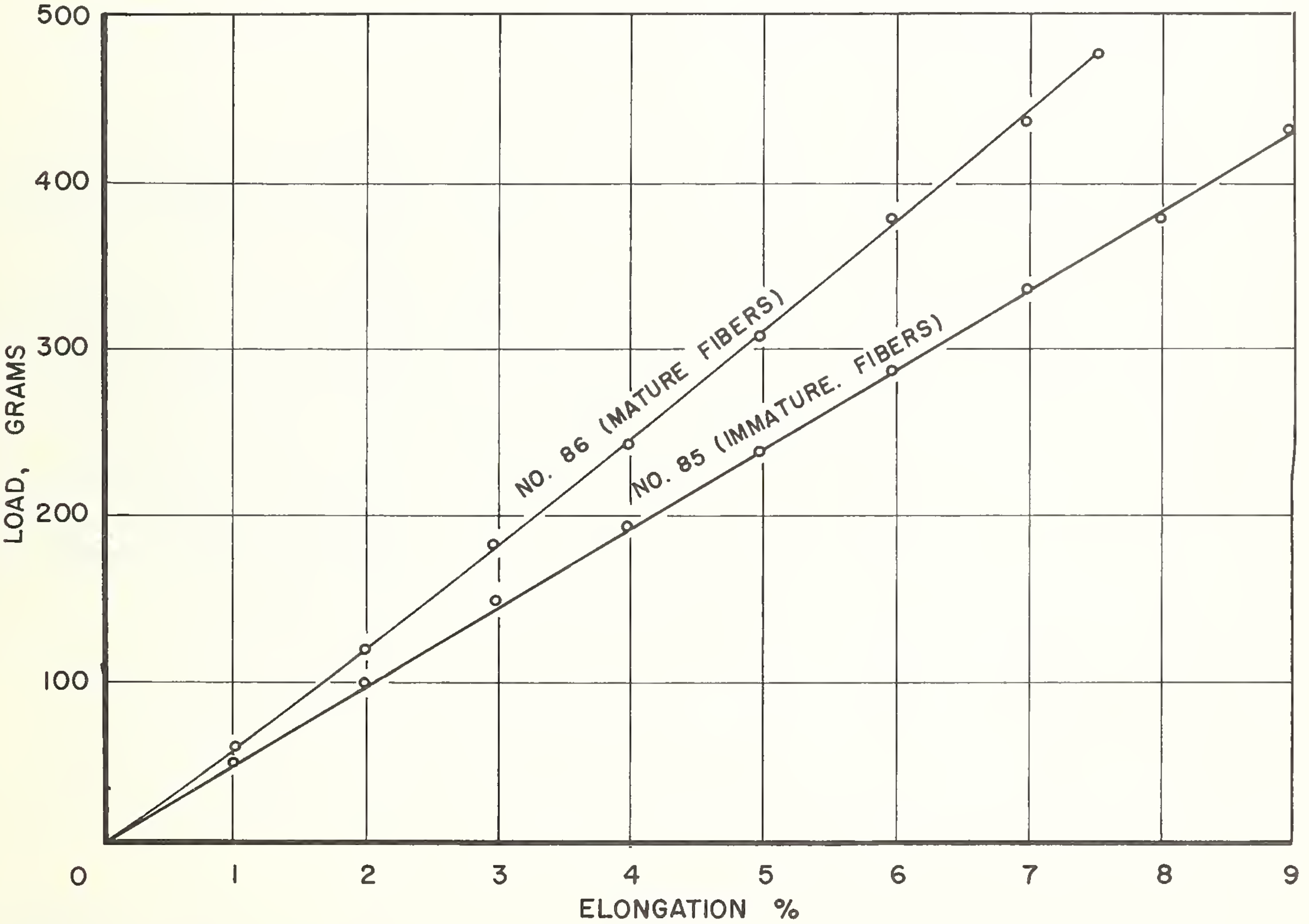
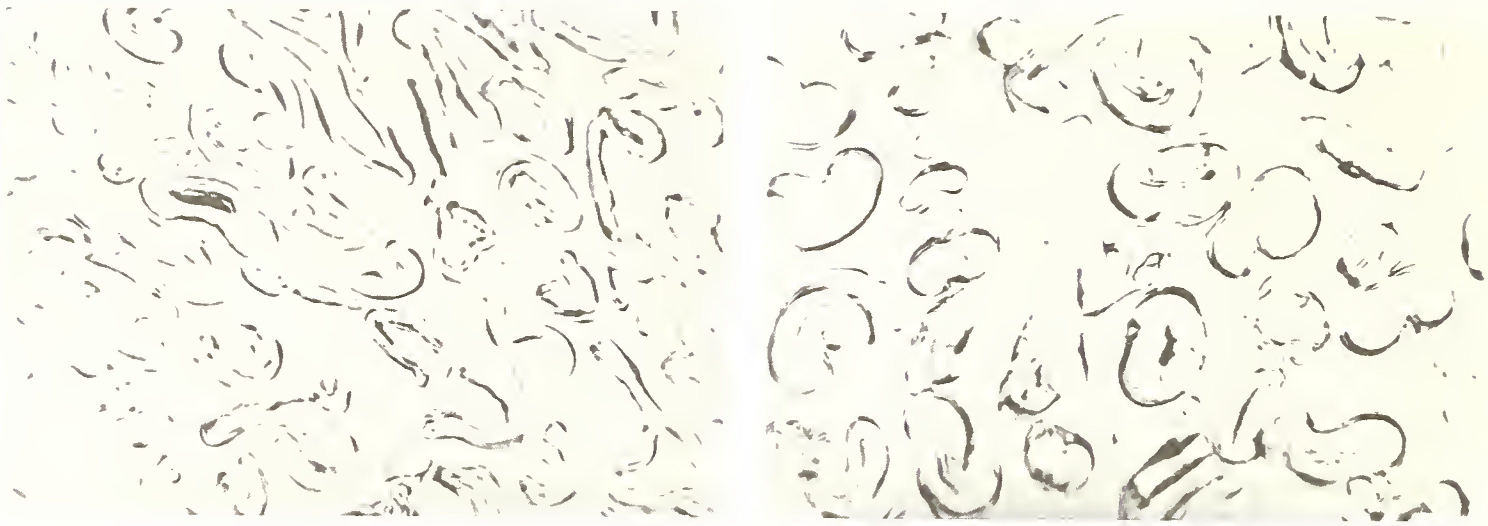


Figure 41.—Load elongation curves of warp yarns from cotton fabrics.


(IMMATURE)
A—Yarn cross section, fabric No. 85 (x750)

(MATURE)
B—Yarn cross section, fabric No. 86 (x750)

Figure 43.—Photomicrographs of yarn cross sections with mature and immature cotton fibers.

mature and immature yarns is in the order of 5 to 4. The effect of the fiber wall thickness on the yarn moment of inertia can be calculated below, with the following assumptions made lest the computations be too involved.

a. The fiber cross sections may be approximated by a rectangle whose dimensions are t x b (Fig. 42.).
b. The openings in the fibers are negligible (Figure 42).
c. The two yarns, having approximately the same yarn numbers (20 and 21), have the same cross-sectional area; i.e., $A_M = N_M \times t_M \times b_M = A_I = N_I \times t_I \times b_I$ where N_M and N_I are the numbers of fibers in each yarn, which assumes the same yarn bulk density.

From assumptions a and b, the fiber moment of inertia is:

$$I_f = \frac{bt^3}{12} \qquad \text{-------------------} (115)$$

The yarn moment of inertia is:

$$I_y = \sum I_f \,\text{[12]} = \frac{Nbt^3}{12} \qquad \text{------} (116)$$

The ratio of yarn moments of inertia is:

$$\frac{I_{y_M}}{I_{y_I}} = \frac{N_M b_M t_M{}^3}{N_I b_I t_I{}^3} \qquad \text{----------} (117)$$

From assumption c, we have:

$$N_M \times t_M \times b_M = N_I \times t_I \times b_I$$

$$\therefore N_M b_M = N_I b_I \frac{t_I}{t_M} \qquad \text{-------} (118)$$

Therefore:

$$\frac{I_{y_M}}{I_{y_I}} = \frac{N_1 b_1 \left(\frac{t_I}{t_M}\right) t_M{}^3}{N_I b_I t_I{}^3} = \left(\frac{t_M}{t_I}\right)^2 \qquad \text{-------} (119)$$

The photomicrographs show that the fiber thicknesses of the mature ones are approximately one and one half times the immature ones. Thus, the ratio of the yarn moments of inertia becomes $(1.5)^2 = 2.25$.

The combined effect of the difference in moduli and in moments of inertia can be made apparent by calculating the ratio of Bending Lengths according to Peirce.

$$\frac{C_M}{C_I} = \frac{\left(\frac{E_M I_M}{W_M}\right)^{1/3}}{\left(\frac{E_I I_I}{W_I}\right)^{1/3}} \qquad \text{--------------} (120)$$

---

[12] This formula assumes the most extreme case of each fiber oriented in the yarn with its major axis parallel to the plane of the fabric. The insertion of yarn twist changes this configuration, and results in smaller differences in I_y than those calculated herein using the above formula.

Since the fabric weights are the same, the ratio becomes:

$$\frac{C_M}{C_I} = \left(\frac{E_M I_M}{E_I I_I}\right)^{1/3} = \left(\frac{5}{4} \times 2.25\right)^{1/3} = 1.41$$

Knowing the Drape Coefficients of the two fabrics, it is possible to calculate the effective Bending Lengths from Equations (45) and (47):

$$C = r_o (Q - \beta) \left(\frac{Q - \beta}{112 (1 - Q)}\right)^{1/6} \qquad \text{------ (121)}$$

where:

r_o = sample radius

$Q = \sqrt{\beta^2 + F(1 - \beta^2)}$

$\beta = r_i / r_o$

r_i = radius of support

F = Drape Coefficient

The calculated ratio of the Bending Lengths of the mature and immature fabrics was 1.10. Although this value differs from 1.41 as calculated previously, it further bears out the effect of moduli as well as moment of inertia on drapability.

6. Effect of Finishes

a. Effect of Sizing on Cotton Fabrics. The effect of sizing can be illustrated by the data given in Table 36.

The method of size removal is the standard ASTM method. However, it should be mentioned here that the desized fabrics were dried on a stretching frame to minimize shrinkage. This was done to eliminate any major alterations in the fabric geometry.

In all cases, the desized samples exhibited a considerable improvement in drapability, accompanied by a slight loss in weight.

The effects of sizing are twofold, the major one being the increase in rigidity. The other effect is the addition of weight.

Table 36.—*Effect of Sizing on Drapability and Weight of Cotton Fabrics*

Fabric No.	Before Desizing		After Desizing	
	F [1]	Weight [2]	F [1]	Weight [2]
	Percent	*Oz./sq. yd.*	*Percent*	*Oz./sq. yd.*
49	78.3	3.63	52.7	3.46
50	72.8	3.63	51.7	3.55
51	72.9	3.63	49.9	3.55
62	77.2	3.73	54.0	3.41
63	71.4	2.89	45.3	2.84
64	65.7	2.49	42.6	2.43
65	67.2	2.45	42.1	2.34

[1] % F @ $\beta = 0.5$.

The increase in yarn rigidity owing to warp size is quite obvious. The individual fibers within a yarn are bound together; the resulting resistance to bending will be considerable. The sizing, in addition to its binding action, also will cause an increase in the yarn moment of inertia. Both the binding of fibers and the increase in the moment of inertia are contributors to poor drapability.

The effect of weight of the sizing, on the other hand, operates in the opposite direction, since the weight factor appears in the denominator of the equation. However, it can be seen from Table 36 that the weight reduction following desizing is small (less than 4%), which would increase the fabric stiffness by about 1½%. The improvement in drapability following desizing is, on the average, in excess of 25%.

b. Effect of Water Repellency Finish

An Army vat dyed cotton sateen fabric was treated with Zelan [13] for water repellency. The Drape Coefficients before and after treatments are as follows:

No. 112	Untreated	83.1% [14]
No. 113	Treated	92.7% [14]

The difference in Drape Coefficient of 8.6% is statistically significant. The application of Zelan [13] apparently stiffened the fabric, thereby rendering it less drapable.

c. Effect of Flameproofing

An 8.5 oz. Army cotton twill was treated with two different amounts of a flameproofing resin. The drape test results are listed below:

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[13] Mention of products in this report does not constitute endorsement by the U. S. Department of Agriculture over similar products not mentioned.

[14] % F at = 0.5.

No. 103 Untreated	71.2%
No. 104 Treated with 16% THPC-Resin	90.8%
No. 105 Treated with 18% THPC-Resin	87.2%

Both of the treated fabrics exhibited significantly poorer drapability than the untreated control. The difference in drapability between the 16% resin finished and the 18% resin finished fabrics was found to be statistically significant, yet the improved drapability of the 18% Resin fabric might be due to slight variations in finishing operations.

d. Effect of Crease Resistant Finishes on (Noncotton) Fabric

The effects of urea formaldehyde, "soft" urea formaldehyde, and "modified" urea formaldehyde on the drapability of a 100% spun viscose fabric (junior butcher weave) can be demonstrated by the data in Table 37.

Table 37.—*Effect of Urea Formaldehyde on Drapability of Spun Viscose Fabric*

Fabric No. and Condition	F[1]
	Percent
106 Untreated Greige Goods	85.5
107 Desized and Bleached Greige Goods	32.5
108 Treated with Urea Formaldehyde	60.0
110 Treated with "Soft" Urea Formaldehyde	33.2
111 Treated with "Modified" Urea Formaldehyde	34.8

[1] Percent F at $\beta = 0.5$.

Statistical analysis showed that the drapability of the viscose fabric treated with urea formaldehyde was greatly impaired but no significant change took place when treated with either "soft" urea formaldehyde or "modified" urea formaldehyde.

e. Effect of Cationic Softener

The desized and bleached greige goods (No. 107) of the spun viscose butcher weave fabrics just discussed was also treated with a cationic softener. The Drapemeter results, % F at $\beta = 0.5$ for the treated and untreated fabrics were as follows:

No. 107 Untreated viscose fabric	32.5%
No. 109 Treated with cationic softener	30.5%

The 2% difference in Drape Coefficients of the two fabrics was found to be statistically significant.

f. Effect of Finishes (Conclusions)

In the light of the foregoing parts (a through e) it is obvious that all the finishes studied herein, warp sizing, water repellency finish, flameproofing, and urea formaldehyde impair drapability of fabrics. The "soft" and "modified" urea formaldehyde did not effect any change in drapability. The use of a cationic softener improved drapability. Presuming that the "Soft U-F" and "Modified U-F" treatments actually rendered the spun viscose fabrics acceptably crease-resistant, and that similar results could be obtained on cotton fabrics, then it should be possible to bolster cotton apparel fabrics in their two outstanding functional deficiencies.

D. Conclusions

The research to date on cotton and "model" specimens of other fabrics has yielded some positive conclusions on possible ways of how draping properties of cotton fabrics can be considerably improved.

In general, the drapability of a fabric is dependent on three basic parameters, referred to on many previous occasions; namely Young's Modulus, E; the cross-sectional moment of inertia, I; and the weight, W. These factors play equally important roles in the fiber, yarn, and fabric forms. The effect of these quantities on drapability can be expressed as follows:

$\% F = f(EI/W)$

Better drapability usually results from an optimum combination of relatively low orders of E and I and a high value of W. On this basis, it was speculated that the optimum combination of these variables might be achieved through a selection from the following tabulation of methods for their control:

1. In the Fiber State:
   a. **Low fiber modulus** may be obtained by:
      i. Selection and breeding.
      ii. Use of immature fibers.
      iii. Chemical treatments effecting crystalline disorder or internal lubrication so that there would result an increased strain per unit stress.
   b. **Low fiber cross-sectional moment of inertia** may be obtained by:
      i. Selection and breeding for fibers with optimum cross-sectional shape and wall thickness.
      ii. Use of immature fibers.
2. In the Yarn State:
   a. **Low yarn modulus** may be obtained by:
      i. Addition of crimp to increase effective bending length.
      ii. Use of high twist yarns, increasing the helix angle of the fibers, thereby

increasing the strains per unit stress induced by bending.

      - iii. Swelling and shrinking to disorient the fibers in such a way that the ease of straining the yarn will be increased.

   - b. **Low yarn cross-sectional moments of inertia** may be obtained by:
      - i. Use of very low twist yarns, so that in the fabric the yarns tend to flatten, and freedom of fiber relative motion is enhanced.
      - ii. Use of very high twist yarns, where the circular yarn diameter is reduced to a minimum.
   - c. **High yarn weight** may be obtained by:
      - i. Use of very high twist yarns wherein there would be an increase in fiber length per unit length of yarn.
      - ii. Use of highly crimped fiber, to accomplish the same purpose as c (i) above.
      - iii. Loading the yarn with nonfibrous finishes.

3. In the Fabric State:
   - a. **Low fabric modulus** may be obtained by:
      - i. Use of open weaves, yielding low cover factors, which, in turn, permit greater yarn mobility.
      - ii. Use of long float lengths, as in twill and satin weaves in contrast to plain weave, which reduces the fabric rigidity by lengthening the span between yarn crossovers.
      - iii. Use of high twist yarns which, because of their circularity and hardness, reduce the area of contact between yarns at crossovers.
      - iv. Use of softeners and lubricants.
   - b. **Low fabric cross-sectional moment of inertia** may be obtained by:
      - i. Weaving a thinner fabric (finer yarns).
      - ii. Flattening the yarns by calendering.
   - c. **High fabric weight** may be obtained by:
      - i. Use of coarser yarns, or a greater number of finer yarns, in the direction of hanging.
      - ii. Increasing crimp and hence increasing the length of yarn per unit length of fabric.
      - iii. Loading with nonfibrous finishes.

Verification of many of the above tabulated points has come not only from experimental data obtained during the drape study but has come also from related research on the mechanics of low strain behavior of fabrics during bending or creasing experiments conducted by Fabric Research Laboratories, Inc., under contract to the United States Office of the Quartermaster General. It has been clearly shown that the forces imposed upon the structural elements of a fabric of any length anticipated in normal draping situations are such that strains of less than 1 percent are induced. This means, then, that any geometric variable in the yarn or fabric that increases stiffness or resistance to strain, even very slightly, may markedly decrease drapability. For example, the above tabulation emphasizes the importance of fiber and yarn mobility to drape.

In addition to the obvious factors affecting such mobility, such as tightness of weave and crimp in the yarns, the more subtle effects of yarn compression and the interlocking of the twist in both warp and filling yarns at crossovers may be of vital importance in influencing mobility *under the conditions of low stress that operate during draping.* Another factor that has been shown to affect the ease of fabric bending under low loads is yarn buckling. While the factors influencing yarn buckling are not clearly defined, the low strain studies emphasize the need to observe yarn buckling during any evaluation of a fabric, if its drape performance is to be understood. Finally, it has been noted that during any bending of a fabric, the yarns in the zone of maximum stress concentration move by trellising. Again, as with buckling, the factors affecting trellising are not clearly defined but the importance of the action is undeniable. Any study of drape should attempt to correlate the ease of trellising with yarn and fabric geometry.

VI. FUTURE WORK

It is immediately obvious from the foregoing that the research to date has been successful in the sense that the measurement of drape has been achieved and considerable advances in the understanding of the mechanics of drape have been made. The time is now right to shift the emphasis of the work from basic mechanics to the application and validation of the principles that have been advanced. It is necessary to determine wherever possible the magnitude of effect of each variable tabulated in the previous section. It is also necessary to evaluate these effects in terms of their practical utility in the actual manufacture of cotton textiles. Therefore, it is proposed that in the future major attention be given to the problems of:

1. Applying the principles of the mechanics of drape to the engineering design of cotton fabrics with improved drape performance.
2. Evaluating simultaneously with the designing of the fabrics, the feasibility of utilizing the proposed new methods in commercial practice.

It should be pointed out here that the future phase of research is not meant to exclude any further exploration of basic factors influencing drape, as such factors become newly defined or as the importance of factors already described assumes new significance because of additional information. It is not claimed that all the variables governing drape have been uncovered completely or related fully. Rather, it is felt that sufficient clarification of the mechanics of drape exists, as a result of the work reviewed in this paper, to permit an intelligent program of application research to take precedence.

With the above considerations in mind, it is proposed that the future research be divided into three distinct portions.

A. Application of Variations in Cotton Fiber

1. **Untreated Fibers:** Among the large number of commercial and experimental varieties of cotton, there exists a wide variation in staple length, wall thickness, cellulose orientation, cross-sectional shape; other variables such as degrees of immaturity can be controlled to some degree by the time and position of picking. The physical properties of a selected number of these cotton varieties, grown under several different conditions, should be measured to categorize their potential effect on the drape of fabric made from each variety. The prediction of drape effects based on fiber properties should then be tested by spinning yarns over a range of twists and weaving fabrics over a range of constructions. The design of the yarns and fabrics should be governed by those geometric factors tending to decrease the modulus and cross-sectional moment of inertia. Ultimately, Drape Coefficients of the fabrics should be measured and the data from fiber, yarn, and fabric correlated.

The objective of this study is, of course, to determine whether it is feasible to improve drape in cotton textiles by supplying the manufacturer with the proper raw material and thus eliminate any need on his part to deviate from standard practice. To make this study possible, some means of discriminating among the many cottons now in use must be found. To this end, it is suggested that the stress-strain data on cotton varieties being assembled at the Textile Research Institute, Princeton, N. J., be used as the basis of choice, along with information on cellulose orientation, fineness, immaturity, etc., available in the files of the U. S. Department of Agriculture.

2. **Treated Fibers:** It has been indicated that the modulus of cotton fibers might be reduced by some treatment which disorders the crystalline structure of the cell wall. It is proposed that this treatment phase of the study examine this possibility. Fabric Research Laboratories, Inc., have been advised that the Southern Utilization Research and Development Division of the USDA Agricultural Research Service has produced some chemically modified cottons of this type. For this study it would be necessary that samples of these modified cottons be made available. Further, depending upon how inclusive the SURDD treatments have been, various additional chemical treatments might be applied to cotton and their effects evaluated.

Whether or not Phase A 1 or A 2 can actually be prosecuted, irrespective of the logic and desirability of conducting such studies, depends upon several circumstances. First, the assumption that a reasonable number of samples can be selected for tudy must be tested by means of discussion with USDA and the Textile Research Institute personnel along with examination of available fiber data. Second, assuming a selection of test varieties can be made intelligently, enough fiber must be available, unquestionably representative of the data upon which the choice were made, to spin yarns and weave fabric. Third, it is possible that not only must the total stress-strain relationships of each variety be known but also desirable that an analysis be made of the low strain portion of the stress-strain curves. At the present time, Fabric Research Laboratories, Inc., have not adapted their low strain techniques to the study of fibers as short as cotton. This means, therefore, that this phase of the program if deemed pertinent must include activities to cover this refinement of technique.

B. Application of Variations in Yarn and Fabric Geometry

Whether or not new and superior raw materials can be supplied to the manufacturer, the question remains: Can readily made changes in spinning and weaving procedures effect improved drape? This leads logically to the question as to what variables potentially relevant to drape are easily varied during spinning and weaving.

During spinning, the following changes can be induced, each over a range:

1. Yarn weight (and diameter).
2. Yarn twist.
3. Percent of fibers of different properties (blending).
4. Fiber orientation (combing).
5. Percent pickup of auxiliaries such as lubricating oils, humectants, antistatic agents.

During weaving and preparation for weaving, the following changes can be induced:

1. Percent and type of finishes on the warp yarns.
2. Tensions on the warp during weaving.
3. Relationship between warp and filling yarns:
    a. Relative sizes.
    b. Relative position (weave).
    c. Relationship of twist, e.g., both Z, one S, one Z, etc.

It is proposed to systematically study yarns, first, and to classify the contribution of the several yarn variables in terms of modulus, moment of inertia, and changes in weight within a count. It is then proposed to select the best yarns and systematically vary the weaving procedures, classifying the resultant fabrics on the basis of Drape Coefficient. During all analyses of drape, constant attention should be focused on the relationships existing between the actual drape measurement and physical phenomena such as yarn buckling, interlocking of twist at yarn crossover, and trellising $\frac{1}{M}$ to clarify the results and to redirect the experimental design, if necessary, along logically dictated lines. Parenthetically, it should be noted that as a result of these studies, it may be possible not only to improve drape but also to improve crease resistance, since both phenomena seem dependent on many of the physical properties common to yarn and fabric.

C. Application of Variations in Finishing

In addition to the introduction of special auxiliaries during spinning and weaving, it is proposed to study the effect of lubricants and other materials added to the fabric after weaving in an attempt to increase yarn mobility and to increase weight. Furthermore, it is planned that the flattening action of calendar rolls and various methods of shrinking fabrics be evaluated as methods of reducing either modulus or moment of inertia.

To conclude, it is important that experimental data on most phases of drape research already exist as a basis for these recommended experiments and interpretations of the results.

APPENDIX

A. Agreement Among Subjects Themselves

Sample Calculation: Stiffness Ranking of Chemical Laboratory Personnel 22 subjects.

FABRIC NUMBER

47	46	23	28	26	34	22	15	14	19
1	2	6	5	3	4	8	7	9	10
1	4	2	6	3	5	8	7	9	10
1	2	3	7	6	4	5	8	9	10
1	2	6	3	4	5	7	9	8	10
1	2	6	4	3	5	8	7	9	10
1	2	5	4	3	6	8	7	9	10
2	1	5	6	3	4	7	8	9	10
1	2	3	8	9	6	5	4	7	10
1	2	6	5	4	3	7	8	9	10
1	2	3	4	6	7	8	5	9	10
1	2	7	5	6	3	8	4	9	10
1	2	6	3	5	4	8	7	9	10
1	2	5	6	3	4	7	8	9	10
1	2	3	6	4	5	7	8	9	10
1	2	6	5	3	4	7	9	8	10
1	3	2	5	6	4	7	8	9	10
1	2	6	3	5	4	7	8	9	10
1	3	2	4	7	5	9	6	8	10
1	2	6	3	4	5	8	7	9	10
5	1	2	7	9	4	8	3	6	10
1	2	7	4	3	5	8	6	9	10
1	2	8	5	3	4	7	6	9	10

u = 27 46 105 108 102 100 162 150 190 220

u^2 = 729 2116 11025 11664 10404 10000 26244 22500 36100 48400

$\Sigma u = 1210$ $(\Sigma u)^2 = 1{,}464{,}100$

$\Sigma u^2 = 179{,}182$

n — No. of samples = 10

m = No. of subjects = 22

w = Concordance coefficient

$$S = \sum u^2 - \frac{(\sum u)^2}{n} = 179182 - 146410 = 32772$$

$$W = \frac{12S}{m^2(n^3 - n)} = \frac{12 \times 32772}{(22)^2(990)} = 0.821$$

$$Z = \frac{1}{2} \ln \frac{(m - 1)W}{1 - W} = \frac{1}{2} \ln \frac{(21 \times 0.821)}{0.179} = 2.28$$

$$n_1 = (n - 1) - \frac{2}{m} = 9 - \frac{2}{22} = 8.09$$

$$n_2 = n_1(m - 1) = 8.09 \times 21 = 169.9$$

$$F_1 = n_1 - 1 = 7.09$$

$$F_2 = n_2 - 1 = 168.9$$

$$Z_c = < 0.6$$

Since Z = 2.28, its value is greater than that of Z = 0.6, and the rankings are significantly alike.

Reference: Winn, L. J. Schwarz, E. R., "Technical Evaluation of Textiles Finishing Treatments III. Use of Rank Correlation for Comparison of Data," Textile Research Journal, 10: 453, September 1940.

B. Comparison of Subjective Rankings vs. Drapemeter Rankings (and/or Strip Bending Test)

I. Subject Stiffness Rankings

1. Strip Bending Test 1 2 3 4 5 6 7 8 9 10

Chemistry Laboratory Personnel 1 2 5 6 4 3 8 7 9 10

$K = 9 + 8 + 5 + 4 + 4 + 4 + 2 + 2 + 1 + 0 = 39$

$$\sum = 2K - \frac{n(n - 1)}{2} = 78 - \frac{10 \times 9}{2} = 33$$

$$T = \frac{2\sum}{n(n - 1)} = \frac{66}{10 \times 9} = 0.733$$

$$t = T\sqrt{\frac{n - 2}{1 - T^2}} = 0.73\sqrt{\frac{8}{0.467}} = 3.04$$

t_c at 0.05 level = 1.86

$t > t_c$, Rankings are significantly alike.

2.

Strip Bending Test	1	2	3	4	5	6	7	8	9	10
Textile Teachers	1	2	6	3	4	5	8	7	9	10

$$K = 9 + 8 + 4 + 6 + 5 + 4 + 2 + 2 + 1 + 0 = 41$$

$$\sum = 2K - \frac{n(n-1)}{2} = 82 - \frac{10 \times 9}{2} = 37$$

$$T = \frac{2\sum}{n(n-1)} = \frac{74}{10 \times 9} = 0.822$$

$$t = T\sqrt{\frac{n-2}{1-T^2}} = 0.82\sqrt{\frac{8}{0.324}} = 4.09$$

t_c at 0.05 level $= 1.86$

$t > t_c$, △ Rankings are significantly alike.

3.

Strip Bending Test	1	2	3	4	5	6	7	8	9	10
Department Store	1	2	6	4	3	5	8	7	9	10

$$K = 9 + 8 + 4 + 5 + 5 + 4 + 2 + 2 + 1 + 0 = 40$$

$$\sum = 2K - \frac{n(n-1)}{2} = 80 - \frac{10 \times 9}{2} = 35$$

$$T = \frac{2\sum}{n(n-1)} = \frac{70}{10 \times 9} = 0.778$$

$$t = T\sqrt{\frac{n-2}{1-T^2}} = 0.78\sqrt{\frac{8}{0.395}} = 3.50$$

t_c at 0.05 level $= 1.86$

$t > t_c$, Rankings are significantly alike.

4.

Strip Bending Test.	1	2	3	4	5	6	7	8	9	10
Interior Decorators	1	2	3	4	6	5	8	7	9	10

$$K = 9 + 8 + 7 + 6 + 4 + 4 + 2 + 2 + 1 + 0 = 43$$

$$\sum = 2K - \frac{n(n-1)}{2} = 86 - \frac{10 \times 9}{2} = 41$$

$$T = \frac{2\sum}{n(n-1)} = \frac{82}{10 \times 9} = 0.911$$

$$t = T\sqrt{\frac{n-2}{1-T^2}} = 0.91\sqrt{\frac{8}{0.170}} = 6.24$$

t_c at 0.05 level $= 1.86$

$t > t_c$, Rankings are significantly alike.

5. Strip Bending Test

Strip Bending Test	1	2	3	4	5	6	7	8	9	10	
All 57 Subjects	1	2	6	3	4	5	8	7	9	10	
K =	9+	8+	4+	6+	5+	4+	2+	2+	1+	0	= 41

This ranking is the same as item 2 above

$t = 4.09$

Rankings are significantly alike.

II. Subjective Gracefulness Rankings (#23 ranked over #28)

1. Drapemeter

Drapemeter	1	2	3	4	5	6	7	8	9	10	
Chemistry Laboratory Personnel	6	4	1	3	2	5	7	8	9	10	
K =	4+	5+	7+	5+	5+	4+	3+	2+	1+	0	= 36

$$\Sigma = 2K - \frac{n(n-1)}{2} = 72 - \frac{10 \times 9}{2} = 27$$

$$T = \frac{2\Sigma}{n(n-1)} = \frac{54}{10 \times 9} = 0.60$$

$$t = T\sqrt{\frac{n-2}{1-T^2}} = 0.60\sqrt{\frac{8}{0.640}} = 2.12$$

t_c at 0.05 level $= 1.86$

$t > t_c$, Rankings are significantly alike

2. Drapemeter

Drapemeter	1	2	3	4	5	6	7	8	9	10	
Textile Teachers	1	2	3	4	5	7	9	6	8	10	
K =	9+	8+	7+	6+	5+	3+	1+	2+	1+	0	= 42

$$\Sigma = 2K - \frac{n(n-1)}{2} = 84 - \frac{10 \times 9}{2} = 39$$

$$T = \frac{2\Sigma}{n(n-1)} = \frac{78}{10 \times 9} = 0.867$$

$$t = T\sqrt{\frac{n-2}{1-T^2}} = 0.87\sqrt{\frac{8}{0.249}} = 4.91$$

t_c at 0.05 level $= 1.86$

$t > t_c$, Rankings are significantly alike.

3.

Drapemeter	1	2	3	4	5	6	7	8	9	10		
Department Store	3	2	1	5	4	6	8	7	9	10		
K =	7+	7+	7+	5+	5+	4+	2+	2+	1+	0	=	40

This value of K will give a value of t = 3.50 (see item 3 above).

Rankings are significantly alike.

4.

Drapemeter	1	2	3	4	5	6	7	8	9	10		
Interior Decorators	2	3	1	4	7	6	9	5	8	10		
K =	8+	7+	7+	6+	3+	3+	1+	2+	1+	0	=	38

$$\Sigma = 2K - \frac{n(n-1)}{2} = 76 \quad \frac{10 \times 9}{2} = 31$$

$$T = \frac{2\Sigma}{n(n-1)} = \frac{62}{10 \times 9} = 0.689$$

$$t = T\sqrt{\frac{n-2}{1-T^2}} = 0.69 \sqrt{\frac{8}{0.525}} = 2.69$$

t_c at 0.05 level $= 1.86$

$t > t_c$ Rankings are significantly alike.

5.

Drapemeter	1	2	3	4	5	6	7	8	9	10		
All 57 Subjects	4	2	1	3	5	6	8	7	9	10		
K =	6+	7+	7+	6+	5+	4+	2+	2+	1+	0	=	40

This value of K will give a value of t = 3.50 (see item 3 above).

III. Subjective Gracefulness Rankings (#28 ranked over #23)

1. Chemistry Laboratory Personnel

Drapemeter	1	2	3	4	5	6	7	8	9	10		
Chemistry Laboratory Personnel	6	4	3	1	2	5	7	8	9	10		
K =	4+	5+	5+	6+	5+	4+	3+	2+	1+	0	=	35

$$\Sigma = 2K - \frac{n(n-1)}{2} = 70 - \frac{90}{2} = 25$$

$$T = \frac{2\Sigma}{n(n-1)} = \frac{50}{90} = 0.56$$

$$t = T\sqrt{\frac{n-2}{1-T^2}} = 0.56 \sqrt{\frac{8}{0.686}} = 0.56 \sqrt{11.66} = 1.91$$

t_c at 0.05 level $= 1.86$

$t > t_c$ Rankings are significantly alike.

2. Drapemeter	1	2	3	4	5	6	7	8	9	10
Textile Teachers	1	2	4	3	5	7	9	6	8	10

$K = 9 + 8 + 6 + 6 + 5 + 3 + 1 + 2 + 1 + 0 = 41$

$$\sum = 2K - \frac{n(n-1)}{2} = 82 - \frac{90}{2} = 37$$

$$T = \frac{2\sum}{n(n-1)} = \frac{74}{90} = 0.82$$

$$t = T\sqrt{\frac{n-2}{1-T^2}} = 0.82\sqrt{\frac{8}{0.328}} = 0.82\sqrt{24.4} = 4.05$$

t_c at 0.05 level $= 1.86$

$t > t_c$ Rankings are significantly alike.

3. Drapemeter	1	2	3	4	5	6	7	8	9	10
Department Store	3	2	5	1	4	6	8	7	9	10

$K = 7 + 7 + 5 + 6 + 5 + 4 + 2 + 2 + 1 + 0 = 39$

$$\sum = 2K - \frac{n(n-1)}{2} = 78 - \frac{90}{2} = 33$$

$$T = \frac{2\sum}{n(n-1)} = \frac{66}{90} = 0.73$$

$$t = T\sqrt{\frac{n-2}{1-T^2}} = 0.73\sqrt{\frac{8}{0.467}} = 0.73\sqrt{17.1} = 3.02$$

t_c at 0.05 level $= 1.86$

$t > t_c$, Rankings are significantly alike.

4. Drapemeter	1	2	3	4	5	6	7	8	9	10
Interior Decorators	2	3	4	1	7	6	9	5	8	10

$K = 8 + 7 + 6 + 6 + 3 + 3 + 1 + 2 + 1 + 0 = 37$

$$\sum = 2K - \frac{n(n-1)}{2} = 74 - \frac{90}{2} = 29$$

$$T = \frac{2\sum}{n(n - 1)} = \frac{58}{90} = 0.64$$

$$t = T\sqrt{\frac{n - 2}{1 - T^2}} = 0.64\sqrt{\frac{8}{0.590}} = 0.64\sqrt{13.6} = 2.36$$

t_c at 0.05 level $= 1.86$

$t > t_c$ Rankings are significantly alike.

5. Drapemeter 1 2 3 4 5 6 7 8 9 10

All 57 Subjects 4 2 3 1 5 6 8 7 9 10

$$K = 6 + 7 + 6 + 6 + 5 + 4 + 2 - 2 + 1 + 0 = 39$$

This value of K will give a value of $t = 3.02$ (see item 3 above).

t_c at .0.05 level $= 1.86$

$t > t_c$ Rankings are significantly alike.

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